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Schottky Diode Series Resistance and Thermal Resistance Extraction From S-Parameter and Temperature Controlled *I–V* Measurements

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Abstract—**A new method for extracting the series resistance and thermal resistance of a Schottky diode is presented. The method avoids the inaccuracies caused by the temperature dependence of the saturation current and ideality factor. These are a major concern for traditional extraction methods, especially when the diode under test has a submicrometer anode diameter and is significantly heated up by the bias current. The method uses theoretical models validated with measurements for the temperature-dependent saturation current and ideality factor, and the series resistance values extracted from low-frequency scattering parameter measurements in the high bias current regime. The main focus of this paper is the accurate extraction of the series resistance. For example, the series resistance value extracted with our method for a discrete diode with a 0.8-μm anode diameter is 88% larger than the series resistance extracted using traditional techniques. As a by-product from the extraction algorithm, an estimate for the thermal resistance of the diode is obtained. The method is validated with extensive current–voltage (*I–V*) and scattering parameter measurements of two different commercially available discrete single anode mixer diodes optimized for terahertz operation. *I–V* measurements are performed at several controlled ambient temperatures and scattering parameter measurements at one known ambient temperature.**

Index Terms—**Current–voltage (*I–V*) characteristics, *I–V* parameter extraction, Schottky diode, series resistance, thermal resistance.**

I. INTRODUCTION

THE SERIES resistance of a Schottky diode is a key parameter for the performance of a Schottky-based device, such as a mixer or a frequency multiplier. In order to create a reliable model of the device, the designer needs a diode model with accurate diode parameters, including the series resistance. The thermal resistance of the diode determines how well the heat

generated in the junction is removed from the junction and is a parameter of importance for all semiconductor devices. The effects of these two parameters on the current–voltage (*I–V*) characteristics of a Schottky diode with a small anode area are considerable. They are also difficult to separate since both increase with decreasing anode area and have their strongest effect in the high bias current regime.

The most common way of extracting the series resistance R_S of a Schottky diode is to first perform direct current *I–V* measurements. The series resistance is then extracted with other Schottky parameters such as ideality factor η and saturation current I_S by fitting the theoretical *I–V* equation or some auxiliary function derived from the *I–V* equation to the measured results [1]–[12]. Occasionally, instead of saturation current, the Schottky barrier height is extracted. However, this requires *a priori* knowledge of the anode size. In [13] and [14], the *I–V* characteristics are measured with an audio frequency ac signal and the parameter extraction is performed as explained above. The problem in these methods is that the measurement is much slower than the thermal time constant of the diode, which can be less than 100 ns for submicrometer anodes [15]. This means that the consecutive *I–V* points in one measurement are all measured at different temperatures. In the measurement of Schottky diodes with small anodes (anode diameter around or below 1 μm), self-heating is substantial and results in errors in the extracted *I–V* parameters: in particular, an extracted value for the series resistance, which is less than the actual value [1], [16], [17].

Another method for the extraction of the series resistance is to measure the derivative of the *I–V* curve with an ac signal at high enough frequency to average out the thermal effects and then calculate the series resistance by subtracting the calculated dynamic resistance of the junction. In [18], an LCR meter is used to measure the derivative of the *I–V* curve up to 1 MHz and the series resistance is then calculated from this value. However, accurate estimates for the ideality factor and junction temperature are needed for the correct calculation of the dynamic resistance of the junction, and these parameters are not accurately known as the self-heating effects are not taken into account. The resulting error for larger anodes is negligible, but in submicrometer anode diodes, the difference in the extracted value of the series resistance could be in the order of tens of percents. Furthermore, the 1-MHz measurement frequency is not high enough for diodes with a submicrometer anode diameter and thermal time constant below 100 ns.

Series resistance and other *I–V* parameters can also be extracted from pulsed *I–V* measurements [19]–[21]. If the device-under-test (DUT) is a Schottky diode with a thermal time constant below 100 ns, the pulsed system should provide synchronized source-and-measure capability for pulse lengths in the order of a few tens of nanoseconds. This requires a complicated test setup with dedicated equipment, careful probe selection, and accurate calibration of the cables and interconnects [19]. The authors are not aware of such successful measurements for submicrometer anode Schottky diodes.

Several methods are available for the determination of the thermal resistance of a semiconductor device. These include pulsed measurements [15], [22], methods based on electrical junction temperature measurements [23], and imaging methods [24]. The general idea is to determine the junction temperature and then—with the knowledge of the ambient temperature and power dissipated in the junction—the thermal resistance can be calculated. It is challenging to compare the accuracy or superiority of one method against another as one method is usually better suited for a particular measurement situation than the other, and a fair comparison would require measurement of similar or the same test devices.

In this paper, we present a method for the extraction of Schottky diode series resistance and thermal resistance. The main focus is on the extraction of the series resistance, and an estimate for the thermal resistance is obtained as a by-product of the series resistance extraction method. Our method is based on the combination of *I–V* measurements at different controlled temperatures, theoretical and empirically verified models for the temperature dependencies of the saturation current and ideality factor, and on scattering parameter (*S*-parameter) measurement results. The latter are obtained at a known temperature, at a relatively low frequency (1–2 GHz) and in the high bias current regime (≥ 1 mA). Our method is best suited for Schottky diodes optimized for the operation at terahertz frequencies (0.1–3 THz), which means anode diameters of the order of 1.0 μm or smaller. Diodes for lower operating frequencies are generally so large that the self-heating effect is negligible or very small.

II. SCHOTTKY DIODE *I–V* CHARACTERISTICS

A. Temperature-Dependent I–V Parameters

The current *I* through the Schottky junction according to [25] is

$$I = I_S \left[\exp\left(\frac{q(V - IR_S)}{\eta k T_J} \right) - 1 \right] \approx I_S \exp\left(\frac{q(V - IR_S)}{\eta k T_J} \right) \tag{1}$$

where q is the elementary charge, k is the Boltzmann's constant, T_J is the junction temperature, and V is the applied voltage. With this notation, the voltage over the junction is $V - IR_S$. Usually, the saturation current and ideality factor are assumed to have the same constant values for all *I–V* bias points, and these values are extracted with an estimate for the series resistance by curve fitting (1) [or some auxiliary function derived from (1)] to measured *I–V* characteristics [1]–[14].

However, saturation current and ideality factor are not constants, but have different values in different bias conditions, as
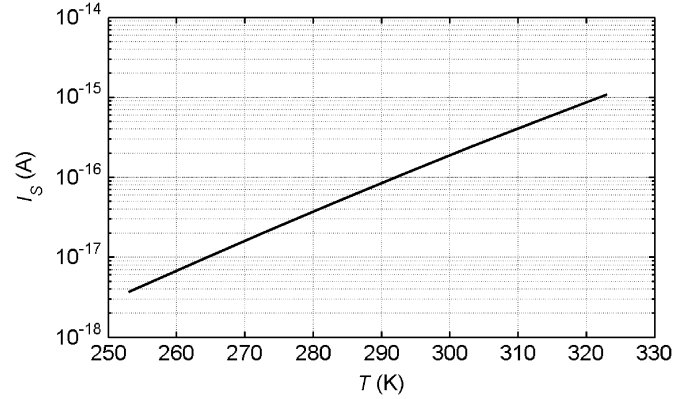

Fig. 1. Illustration of the saturation current as a function of the junction temperature according to (2) and (3). Parameters for the calculation are from an SC2T6 diode used in this study.
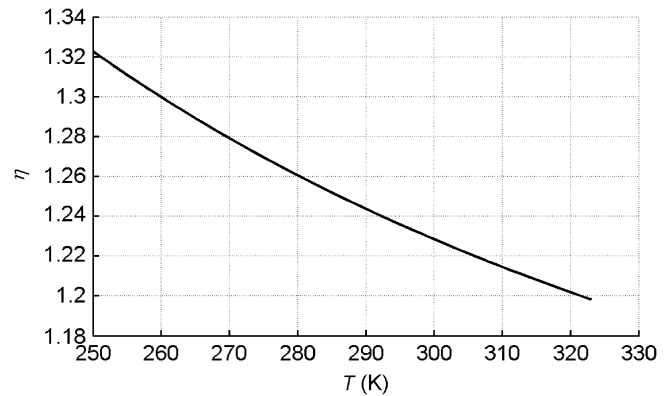

Fig. 2. Illustration of the ideality factor as a function of the junction temperature according to (3). Parameters for the calculation are from an SC2T6 diode used in this study.

the junction is heated by the current flowing through the diode. The temperature dependence of the saturation current and ideality factor as a function of the junction temperature according to [26]–[28] can be expressed as

$$I_S = SA**T_J^2 \exp\left(\frac{-q\Phi_b}{\eta k T_J} \right) \tag{2}$$

$$\eta = \frac{q}{kT_J} E_{00} \coth\left(\frac{qE_{00}}{kT_J} \right) \tag{3}$$

where S is the surface area of the junction, A^{**} is the modified Richardson constant (8.2 Acm^{-2}K^{-2} for GaAs), Φ_b is the height of the Schottky barrier, and E_{00} is a constant with constant doping density. The behavior of the saturation current and ideality factor as a function of temperature is illustrated in Figs. 1 and 2 for an SC2T6 Schottky diode used in this work. In (2), the barrier height is assumed constant. This is an approximation, as the barrier height has a weak bias voltage dependency due to the image-force lowering effect. The error due to the image-force lowering to the thermal resistance and series resistance values extracted with the new method is discussed in Section VI. In addition, the barrier height and modified Richardson constant both experience a weak temperature dependency. This, however, is taken into account in the new method since the extraction is done at known bias points and

temperatures, and estimates for thermal and series resistance are calculated separately in discrete bias points.

B. Self-Heating of the Anode Junction

A model for Schottky junction temperature dependence is given in [17] and [27]. The temperature change in the junction for diodes with a circular anode can be estimated with

$$T_J = T_0 + P_T R_\theta \tag{4}$$
$$P_T = VI = \Phi_b I + R_S I^2 \tag{5}$$
$$R_\theta = \rho_\theta / 4r \tag{6}$$

where T_0 is the ambient temperature, P_T is the power dissipated within the diode, R_θ is the thermal spreading resistance of the diode chip, ρ_θ is the thermal resistivity of GaAs ($22 \cdot 10^{-3}$ Km/W at 300 K), and r is the anode radius. The equation for the thermal resistance (6) is an approximation for the situation where the semiconductor continues indefinitely far from the junction. In reality, the thermal resistance is also determined by other materials and the geometrical structure of the diode and is heavily affected, for example, by the removal of semiconductor material around the anode, which is often done in order to reduce the parasitic electrical capacitance of the diode, but increases the thermal resistance. On the other hand, the thermal performance of the diode can also be enhanced by, for example, having materials with good thermal conductivity near the junction.

When the temperature change of the junction due to the self-heating effect and the temperature dependence of the saturation current and ideality factor is taken into account using (2)–(6), we see that the current level at a given applied voltage is, in fact, larger than that predicted by (1) with constant saturation current and ideality factor. Consequently, if the series resistance extraction is done based on constant values of the saturation current and ideality factor, the extracted value for the series resistance will be lower than the real series resistance of the diode [1], [16], [17]. The same applies if (2) is substituted into (1) and the Schottky barrier height is extracted instead of the saturation current. This is illustrated in Fig. 3, where the I–V curves obtained both with the traditional extraction and with the temperature-dependent model are shown with the resulting error in the extracted value of the series resistance. This effect is more pronounced in diodes with a small anode diameter or in structures where the thermal resistance is increased, e.g., by removing material around the anode, and thus, disturbing the flow of thermal energy away from the junction.

III. NEW EXTRACTION METHOD

Our extraction method for the series resistance and thermal resistance of a Schottky diode uses a combination of temperature controlled I–V measurements and S-parameter measurements at a known ambient temperature. We start by building temperature-dependent models for the saturation current and ideality factor.

A. Temperature-Dependent Models for Saturation Current and Ideality Factor

Saturation current and ideality factor values at different temperatures are extracted and the results are fitted to (2) and (3)
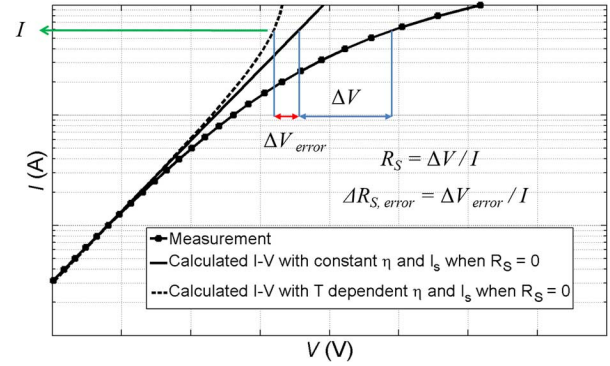

Fig. 3. Extraction of the series resistance and the error caused by the assumption that the saturation current and ideality factor have constant values in all bias points. The data is for illustration purposes only and is calculated with (9) using thermal resistance approximation according to (6).

by solving parameters E_{00}, Φ_b, and the product SA^{**}. The ideality factor and saturation current values are extracted at current levels that are always below 50 μA, i.e., in the linear part of the logarithmic I–V curve. In this current range, the self-heating of the junction is negligible and the junction is in the same temperature as the ambient (temperature-controlled chuck).

Fitting saturation current in this way is essentially the same as performing activation energy method (I–V–T) measurements [28]. The difference is that we do not need exact values for the Schottky barrier height or for the product SA^{**}, but only a model that predicts the temperature dependencies of the saturation current and ideality factor. The temperature-dependent ideality factor is used in the model for the saturation current at corresponding temperature points.

With temperature-dependent models for the saturation current and ideality factor, we can now define a voltage, V_1, across the Schottky junction when the junction is heated up by a known bias current. By using (1) without the series resistance, for the voltage across the junction we get

$$V_1 = \frac{\eta(T_J)kT_J}{q} \ln\left(\frac{I}{I_S(T_J)}\right). \tag{7}$$

In (7), $\eta(T_J)$ is the temperature-dependent ideality factor and $I_S(T_J)$ is the temperature-dependent saturation current. As illustrated in Fig. 3, the real series resistance can be calculated as

$$R_S = \frac{\Delta V_{\text{error}} + \Delta V}{I}. \tag{8}$$

With the temperature-dependent junction voltage definition in (7), this can be written as

$$R_S = \frac{V - V_1}{I} = \frac{V}{I} - \frac{\eta(T_J)kT_J}{qI} \ln\left(\frac{I}{I_S(T_J)}\right) \tag{9}$$

where V is the voltage over the diode (junction + series resistance) at a current I. By substituting the temperature-dependent models for the saturation current and ideality factor in V_1 and then substituting the junction temperature (4) in these models and in (7), and finally, by substituting (5) for the power dissipated in the junction in (4), we get a formula for the series resistance, where the only unknown variable is the thermal resistance. Equation (6) could now be used to evaluate the thermal

resistance and an estimate for the series resistance could be obtained. However, (6) is only an approximation and is not considered to be accurate enough to describe the thermal resistance of a complicated diode structure. Consequently, more information is needed to obtain an accurate estimate for the thermal resistance and then calculate the value of the series resistance. This information is obtained from low-frequency S-parameter measurement results of the Schottky diode in the high bias current regime.

B. Extraction of the Total Resistance of the Diode From S-Parameter Measurements

When a diode is biased to high current levels (≥ 1 mA), the junction is conducting and the dynamic resistance is of the same order as the series resistance. By applying a small ac signal and measuring the reflected and transmitted power, the derivative of the I–V curve, i.e., the small signal conductance, $g(I)$, can be obtained. It should be noted here that the small-signal conductance measured with an ac signal at a high enough frequency is not the same as the derivative of the I–V curve measured with traditional dc measurements because in the direct current measurement the consecutive I–V points are at different temperatures. The relationship between the small-signal conductance and the series resistance is

$$g(I) = \frac{1}{r_j + R_S} = \frac{1}{\frac{\eta(T_J)kT_J}{qI} + R_S} = \frac{1}{r_T} \qquad (10)$$

where r_j is the dynamic resistance of the junction and r_T is the total resistance of the diode, which is the inverse of the small-signal conductance. There are, however, several conditions for the ac signal for (10) to be an accurate description of the small-signal conductance and these are as follows.
  1) The ac signal must be so small that it does not heat up the junction from the quiescent bias point.
  2) The ac signal must be at a high enough frequency to average out the thermal effects.
  3) The ac signal must be at low enough frequency so the diode can be approximated with a single component (total resistance, r_T).

Condition 1) is easily fulfilled by choosing a small ac signal. In our study, the ac power is always kept below -25 dBm and heats up the junction less than 0.1 K according to our results or calculated using (4)–(6). In order to comply with conditions 2) and 3), the signal frequency must be selected to be much more than 10 MHz as the thermal time constant is assumed to be less than 100 ns. On the other hand, the signal frequency should not be much more than 10 GHz because, in that case, the junction and parasitic capacitances of the diode should be taken into account and the error in the estimation of these elements is transferred into an error in the estimation of the small-signal conductance, and hence, in the error in the estimation of the series resistance. We choose the frequency range of 1–2 GHz for the extraction of the total resistance. In this frequency range, the rise/fall time of the signal is less than 1 ns and the junction will not react thermally. On the other hand, at this electrically

TABLE I
DIODE I–V AND C–V PARAMETERS AND CUTOFF FREQUENCY

Parameter	IMSQ08	SC2T6
I_S (fA)	0.15	0.10
η	1.27	1.24
$R_S(\Omega)$ [(1)]	5.9	4.5
C_{j0} (fF)	1.29	1.81
C_p (fF)	5.58	8.55
Φ_{bi} (V)	0.97	0.77
f_c (THz)	20.9	19.5

[(1)] Series resistance extracted with traditional extraction technique at 5 mA.

relatively low frequency, the diode can be extremely well approximated with a single resistor with short pieces of coplanar waveguide (CPW) on both sides to account for the test structure (length of each piece is around 650–700 μm, depending on the diode and position where the diode is soldered). For example, between 1–2 GHz, the extracted value for the total resistance differs less than 0.03 Ω from the value that is obtained by extracting this value from a complete equivalent circuit of the diode with the parameters given in Table I. At 10 GHz, this difference is already 0.73 Ω. Also any changes in the resistance caused by the skin effect will be negligible in the selected frequency range.

C. Solving the Thermal Resistance and Series Resistance

To summarize, the total resistance, which is the sum of the temperature-dependent junction resistance and the series resistance, is extracted from S-parameter measurement results by fitting the calculated reflection and transmission coefficients to the measured ones in the frequency range of 1–2 GHz at bias current points of 1 and 5 mA. The junction temperature and the temperature-dependent ideality factor in (10) can also be expressed as a function of the thermal resistance by substituting (4) and (5) in place of the junction temperature.

By combining (9) and (10), we can eliminate R_S, which leads to the following equation:

$$\frac{V}{I} - \frac{\eta(T_J)kT_J}{qI} \ln\left(\frac{I}{I_S(T_J)}\right) = r_T - \frac{\eta(T_J)kT_J}{qI} \qquad (11)$$

where, after the substitution of (2)–(5), the only unknown in the equation is the thermal resistance R_θ, which can then be solved numerically. With a value for the thermal resistance, the series resistance can now be solved with (9) or with (10) by substituting the obtained value for the thermal resistance in (2)–(5). Equation (10) is used for the extraction of the series resistance values in Table II, as it is less sensitive for a possible error in the estimate of the thermal resistance, as will be shown in Section VI. By combining I–V and S-parameter measurement results, we have now solved the thermal resistance and series resistance values for a Schottky diode at the desired bias current points.

TABLE II
DIODE PARAMETERS EXTRACTED WITH THE TRADITIONAL
METHOD AND WITH THE NEW METHOD

I (mA)	Parameter	IMSQ08	SC2T6
1.0	T_J (K)	302	298
	R_θ (K/W)	9170	4800
	R_S (Ω) [1]	8.4	7.4
	R_S (Ω) [2]	14.1	9.8
5.0	T_J (K)	348	321
	R_θ (K/W)	10570	5620
	R_S (Ω) [1]	5.9	4.5
	R_S (Ω) [2]	11.1	6.8

[1] Series resistance extracted with traditional extraction technique.
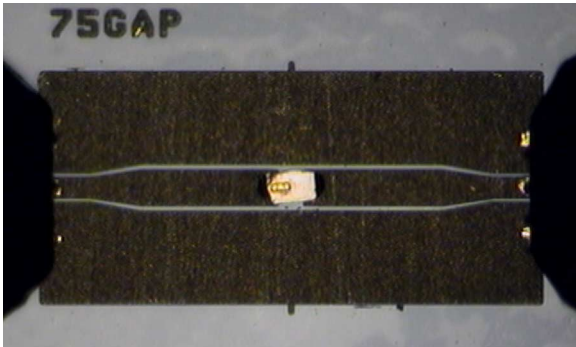[2] Series resistance extracted with our extraction technique.

Fig. 4. IMSQ08 Schottky diode attached to a CPW center conductor on a quartz carrier substrate. The center conductor width at the center is 110 and 66 μm at the ends of the test structure and the center conductor to ground spacing is 15 μm at the center and 10 μm at the ends. The gap for the diode is 75-μm wide. The total width of the CPW test structure is 1500 μm. Metallization is gold with a thickness of 3 μm.

IV. DIODES UNDER TEST AND MEASUREMENT SETUP

To demonstrate our method, we measured several mixer diodes from two manufacturers. A single anode Schottky diode IMSQ08 from Advanced Compound Semiconductor Technologies (ACST), Darmstadt, Germany, and a single anode Schottky diode SC2T6 from Virginia Diodes Inc. (VDI), Charlottesville, VA. The anode radii are approximately 0.4 μm for the IMSQ08 diode and 0.7 μm for the SC2T6 diode. Knowledge of the exact anode radius or size is not necessary for the use of our method, but an approximate value is helpful for estimating whether or not the thermal effects are significant for a given type of diode.

For the tests, the diodes were flip-chip soldered on a coplanar quartz carrier substrate and the contact to the carrier was made with Cascade Microtech Infinity probes with 150-μm pitch. Fig. 4 shows an IMSQ08 diode on a quartz carrier 6.8 and contact probes. The quartz carrier was placed on a temperature-controlled chuck of the Cascade Microtech probe station and the temperature was adjusted with a Temptronic Corporation Thermal Platform.

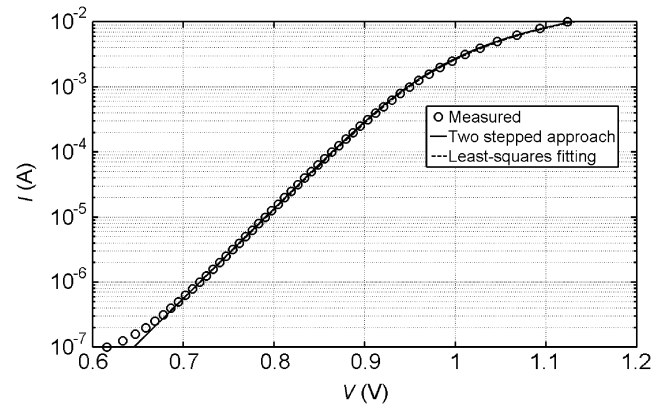The I–V measurements were conducted with an Agilent 4156C Precision Semiconductor Parameter Analyzer in the

Fig. 5. Measured I–V characteristics and calculated I–V characteristics using traditional two-step approach and least squares curve fitting algorithms. The data is for an SC2T6 diode.

temperature range of 253–323 K with a 10-K step. The current range in the measurements was 10 fA–10 mA with a logarithmic current step. The dc resistance of the contact wiring and probes was measured using a CPW thru piece. The S-parameters were measured with an Agilent N5250 PNA at 0.1–110 GHz at an ambient temperature of 293 K in several bias voltage points between $-3, \ldots, 0.5$ V and at bias current points of 1 and 5 mA. The small-signal power was kept under -25 dBm at all times. Before the measurements, the system was calibrated at the probe tips using a Cascade Microtech line-reflect-reflect-match (LRRM) calibration kit. A CPW thru piece was also measured in order to create a model for the CPW transmission line, which is used with the diode model to take into account the short pieces of CPW on both sides of the diode on the test structure.

V. TRADITIONAL I–V EXTRACTION RESULTS

The I–V parameters shown in Table I are extracted from measurements done at 293 K with a two-step method [1]. The saturation current and ideality factor values are first extracted with the traditional extraction method in the part of the I–V curve, where the effect of the self-heating and the effect of the series resistance are negligible. After that, the series resistance is calculated as the difference between measured results and ideal diode characteristics at 5-mA bias current. The I–V parameters were also extracted with a least squares fitting algorithm [7]. It was found that the difference of the methods on the extracted I–V parameters is negligible if the highest current point used in the least squares fitting is the same as the current point where the series resistance is calculated with the two-step method. This is illustrated in Fig. 5, where the I–V curves calculated with both methods for the SC2T6 diode are shown with the measured results.

In order to establish the high-frequency capabilities of the diodes, we also extracted the capacitance–voltage (C–V) parameters from S-parameter measurement results at negative and small positive bias voltages (≤ 0.5 V). The C–V parameters are zero bias junction capacitance C_{j0}, parasitic parallel capacitance C_p, and built-in voltage Φ_{bi}. Diodes from the same manufacturer are very similar in performance. I–V and C–V parameters and the cutoff frequency $f_c = 1/2\pi R_S C_{j0}$ for one IMSQ08
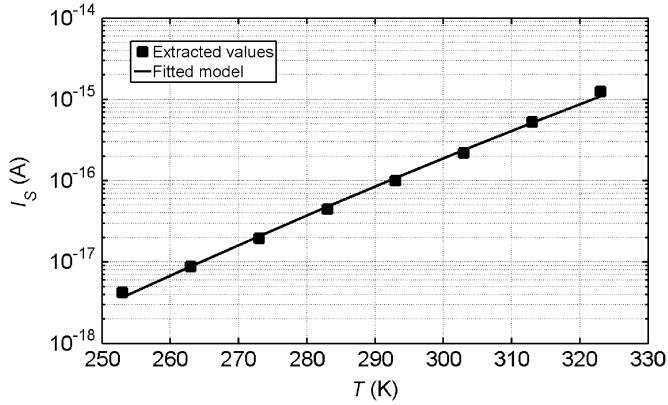
Fig. 6. Extracted values of the saturation current at different temperatures with the fitted model. The data is from an SC2T6 diode.
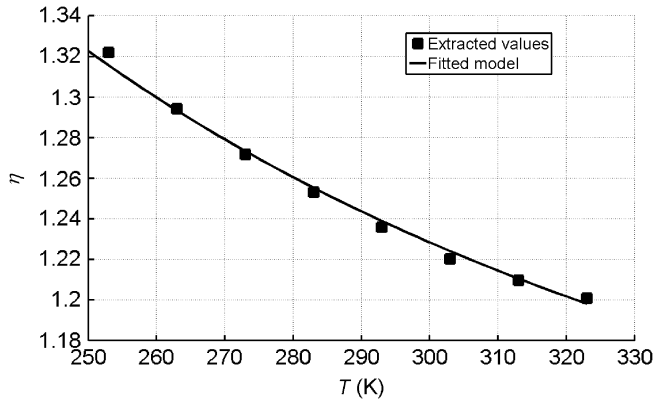

Fig. 7. Extracted values of the ideality factor at different temperatures with the fitted model. The data is from an SC2T6 diode.

Fig. 8. Series resistance values calculated using (9) and traditional extraction methods for an IMSQ08 diode, including the lower and upper error limits showing the effect of a ±30% error in the extracted value of the thermal resistance.

diode and one SC2T6 diode are given in Table I. The data used in the examples of this paper is also from these two diodes.

Here these methods are referred to as traditional extraction methods. In the latter part of this paper, we will show that the difference in the extracted value of the series resistance obtained using either the traditional methods or our method is significant. The reason for this is that the assumption made in the traditional *I–V* parameter extraction—junction temperature, saturation current, and ideality factor have the same constant values in all bias points—is not physically valid, as is explained in Section II.

VI. NEW EXTRACTION METHOD RESULTS

By applying the method of parameter extraction described in Section III to the measurement results of our test diodes, we have created temperature-dependent models for the saturation current and ideality factor. Results from the model and the extracted values are shown in Figs. 6 and 7. With these models and with the total resistance values extracted from *S*-parameter measurement results, we have solved the junction temperature, thermal resistance, and series resistance at 1- and 5-mA bias points. The results from the extraction are summarized in Table II.

From the data, it can be seen that the extracted junction temperature is larger in the diode with a smaller anode than in the diode with a larger anode. The junction temperature is also higher at a larger bias current and the thermal resistance is larger
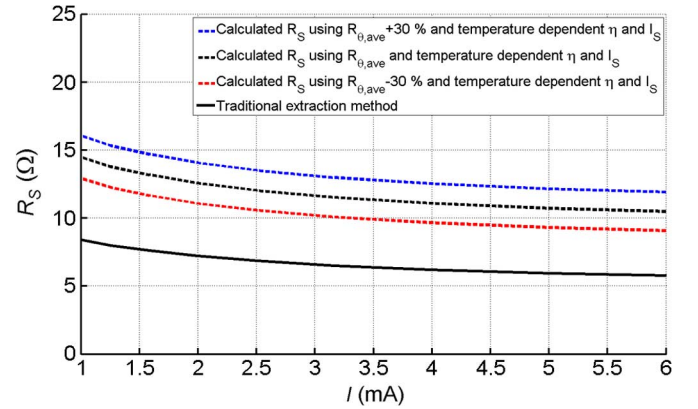
in the diode with a smaller anode, as expected according to (6). Furthermore, the extracted thermal resistance value is smaller at lower temperatures, which is also congruent with the theoretical nonlinear behavior of the thermal conductivity of GaAs [30]. Finally, the series resistance values extracted with our method are considerably larger than the values extracted using traditional extraction techniques that do not take into account the temperature-dependent *I–V* parameters. For example, at a 5-mA bias current point, the difference in series resistances is 88% for an IMSQ08 diode and 51% for an SC2T6 diode.

A possible source of error for the extraction of the thermal resistance is the temperature-dependent model for the saturation current. The saturation current model is extracted from measurements around a 0.8-V $(10^{-5}$ A$)$ bias voltage (current) point and the Schottky barrier height in the model corresponds to that voltage. However, the Schottky barrier height is not constant, but experiences a so-called "image force lowering" effect caused by the electric field in the semiconductor [27]. As the image force lowering is proportional to the square root of the maximum electric field in the semiconductor junction and the voltage over the junction in the high bias current regime is around 0.95 V, we can approximate the error in the image force lowering to be less than 9% or ∼3 mV assuming that the total image force lowering is ∼30 mV [27]. Without the knowledge of the thickness of the epilayer, it is impossible to give an accurate estimation for the image force lowering.

Based on the above-mentioned error caused by the image force lowering, the resulting difference in the estimate for the thermal resistance at 5-mA bias point would be less than 20% for both diodes. Assuming this and allowing some room for measurement uncertainty, a ±30% error in the estimate of the thermal resistance is used for the extraction of the series resistance using either the temperature-dependent model (9) or the total resistance extracted from *S*-parameter measurements (10).

The resulting error using (9) is shown in Fig. 8 for the IMSQ08 diode and in Fig. 9 for the SC2T6 diode as a function of the current point, which is used for the calculation of the series resistance. The thermal resistance value used in the calculation is the average of the values in 1- and 5-mA bias points, which are given in Table II. For example, the relative
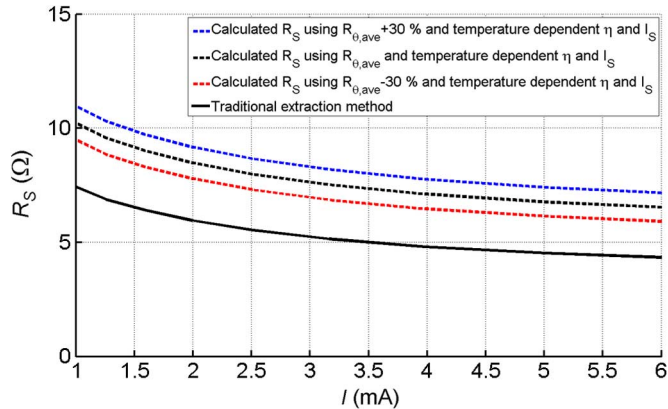
Fig. 9. Series resistance values calculated using (9) and traditional extraction methods for an SC2T6 diode, including the lower and upper error limits showing the effect of a $\pm 30\%$ error in the extracted value of the thermal resistance.

error is $\pm 13.4\%$ ($\pm 1.49\ \Omega$) for the IMSQ08 diode, and $\pm 9.6\%$ ($\pm 0.67\ \Omega$) for the SC2T6 diode at 5 mA.

However, the error using the S-parameter method (10) does not suffer from the image force lowering inaccuracies, or more generally, any inaccuracies in the estimate for the saturation current, as only the ideality factor and junction temperature are considered in the formula. The error using (10) is only $\pm 1.9\%$ ($\pm 0.21\ \Omega$) for the IMSQ08 diode and $\pm 1.6\%$ ($\pm 0.11\ \Omega$) for the SC2T6 diode at a 5-mA bias point. These values are not included in Figs. 8 and 9 as the points would be almost completely overlapping and visually impossible to separate. The series resistance values at 1- and 5-mA bias points are given in Table II.

Extraction from the S-parameter measurement results using (10) is therefore considered to be an extremely accurate method for the determination of the series resistance of Schottky diodes. The extracted value for the series resistance is not sensitive to the possible error in the estimated value of the thermal resistance because the S-parameter measurement averages out the thermal effects that cause errors in traditional extraction techniques. To demonstrate this further, let us assume an extreme $\pm 100\%$ error in the estimate of the thermal resistance. This means that the thermal effect is either removed completely or doubled. The case where the effect is removed, $R_\theta = 0$ K/W, corresponds to the situation, where the junction temperature used in (10) is the ambient temperature and the ideality factor is the one extracted using the traditional method at ambient temperature. With the above $\pm 100\%$ error of the thermal resistance, the resulting error in the extracted value of the series resistance is $\pm 7.1\%$ ($\pm 0.8\ \Omega$) for the IMSQ08 diode and $\pm 6.0\%$ ($\pm 0.4\ \Omega$) for the SC2T6 diode at a 5-mA bias point. This example shows that a good estimate for the series resistance can be obtained even without knowledge of the thermal resistance, as long as the total resistance is extracted from the S-parameter measurement results using (10). If Schottky diodes with even smaller anodes are measured, a good estimate for the thermal resistance becomes more important even when using (10), as the junction temperature differs significantly from the ambient temperature and causes larger error in the calculated value of the series resistance.

VII. DISCUSSION

We have demonstrated the capability of our new method in extraction of the thermal resistance and the series resistance of Schottky diodes. The results using the new method can be readily used in evaluation and comparison of terahertz Schottky diodes with small anode diameters. The traditional extraction of I–V parameters cannot provide the same accuracy for the value of the series resistance because the effect of even a large series resistance can be obscured by the effect of a large thermal resistance. Our method provides accurate values for the series resistance regardless of the value of the thermal resistance and as a by-product an estimate for the thermal resistance.

The ultimate goal in the characterization and modeling of Schottky diodes is obviously to create a reliable circuit model that is valid under large signal conditions and at high (terahertz) frequencies. As the frequency increases, the series resistance increases because of the skin effect. It should be noted here that our model takes into account only the inaccuracies caused by the heating of the junction and not those caused by the skin effect. The determination of the extent of the skin effect is difficult at terahertz frequencies as the measurement accuracy is limited by calibration accuracy and possible inaccuracy in the determination of other equivalent-circuit parameters such as junction and parasitic capacitances and finger inductance. The skin effect can be studied using full-wave simulators [31]. We propose that the series resistance value extracted using our method is used as a baseline and the frequency-dependent increase in the series resistance is calculated using full-wave simulations and added to the baseline value.

VIII. CONCLUSIONS

In this paper, we have presented a method for the extraction of the Schottky diode series resistance and thermal resistance. Our method avoids the uncertainty in the extracted values due to the self-heating of the anode junction, which is not possible with traditional I–V extraction methods using dc or audio frequency ac signal measurements. The method is based on theoretical models validated with measurements for the temperature-dependent saturation current and ideality factor and uses low-frequency S-parameter measurement results in the high bias current regime. In short, the method consists of two parts, first the extraction of the thermal resistance is performed by combining the results from temperature-controlled I–V measurements and from S-parameter measurements. Secondly, the series resistance can be extracted either by comparing the temperature-dependent diode equation to the measured I–V results or by calculating it from the total resistance obtained from S-parameter measurement results.

The extraction of the series resistance from S-parameter measurement results is an extremely accurate process, which is not sensitive to a possible error in the estimate of the thermal resistance. We have demonstrated our method with two commercial single anode Schottky diodes with submicrometer anode radii. We have shown that the obtained values for the series resistance of these diodes are significantly larger than the values obtained with traditional extraction techniques. For the diode

with a smaller anode, the difference is 88% when the extraction is done at a 5-mA bias point. For smaller anodes, this effect is even more pronounced and might be a significant cause for error in the design of a submillimeter-wave mixer or multiplier circuits using Schottky diodes.

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