Invited Paper

Schottky diode characterization, modelling and design for THz front-ends

Tero Kiuru *
VTT Technical Research Centre of Finland, Communication systems
P.O Box 1000, FI-02044 VTT, Finland
* Email: tero.kiuru@vtt.fi

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Abstract: Efficient characterization and modelling techniques have a key role in the development of Schottky diode-based devices with state-of-the-art performance. This paper makes an effort to introduce such techniques and to provide examples of how they are used by the Schottky community. The modelling techniques covered in the paper are circuit simulator and electro-magnetic modelling. Characterization methods include current-voltage, capacitance-voltage, S-parameter, test jig-based, and thermal measurement techniques.

Keywords: Schottky diode, Modelling, Characterization, S-parameters, I-V measurements, C-V measurements, Thermal characterization

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1. Introduction

The Schottky diode is the workhorse in almost all non-cryogenic mixer and multiplier applications at THz (100-3000 *GHz*) frequencies [1, 2]. Nowadays, it is increasingly used also for direct detection [3]. Squeezing out the last drop of efficiency from the Schottky-based devices requires accurate characterization and modelling techniques. This paper introduces the most widely used approaches, with emphasis on the circuit design and RF performance.

This paper concentrates on the practical aspects of modelling and characterization methods, including I-V, C-V and S-parameter measurements as well as circuit simulator and 3D electromagnetic simulation approaches. Two less used, yet efficient, characterization methods are also presented: thermal characterization and test jig measurements. It should be noted that the list of modelling and characterization techniques is by no means exhaustive. Some interesting topics not covered here due to space and page constraints are a multitude of wafer level characterization techniques [4], low-frequency noise measurements [5], and physical modelling [6].

We present several modelling and measurement results in the paper. All the electrical measurement examples in this paper use a SC2T6 single-anode Schottky diode from Virginia Diodes Inc., Charlottesville, VA, USA. The thermal measurements are performed for a single-anode multiplier diode from Chalmers University of Technology, Göteborg, Sweden. If not otherwise stated, the diodes are soldered on a coplanar waveguide (CPW) carrier as shown in Fig. 1 [7]. This paper is based on a review conference paper by the author [8] with added material on THz front-end implementation using Schottky diodes.

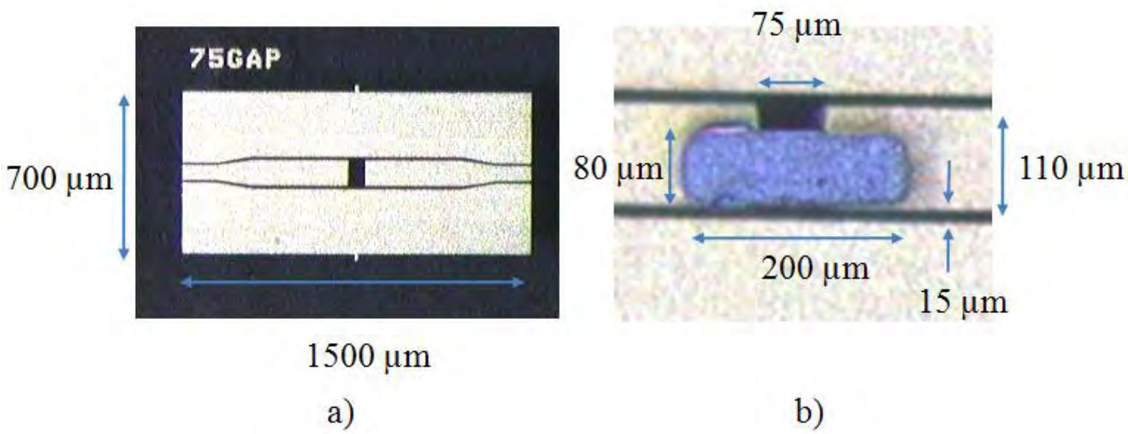


Fig. 1 Photographs of a) the test carrier for discrete diodes and b) diode attached on the carrier.

2. THz front-end

In order to understand how Schottky diodes are used at THz frequencies and why it is so important to model and characterize them accurately, one must understand the basics of receiver front-ends that are used at those frequencies. A simple schematic presentation of a THz receiver front-end is shown in Fig. 2.

Starting from the left, the receiver needs an antenna to pick up the RF signal. After the antenna, the signal travels through a transmission line, typically a waveguide or quasi-optical system, to the first solid-state component. Depending on the frequency, this component is a low-noise amplifier or a mixer. Amplifiers are available approximately below 200 *GHz* and, therefore, above this frequency the first component is almost always a mixer. The quality (conversion loss and noise temperature) of this mixer largely determines the quality of the receiver. In order to work well, the mixer needs stable and low-noise local oscillator (LO) power. By using this LO signal, the RF signal is downconverted and then fed to the IF section of the receiver and after that to the detection circuitry.

In THz receivers, both mixer and local oscillator chain last multipliers are typically build using Schottky diodes.

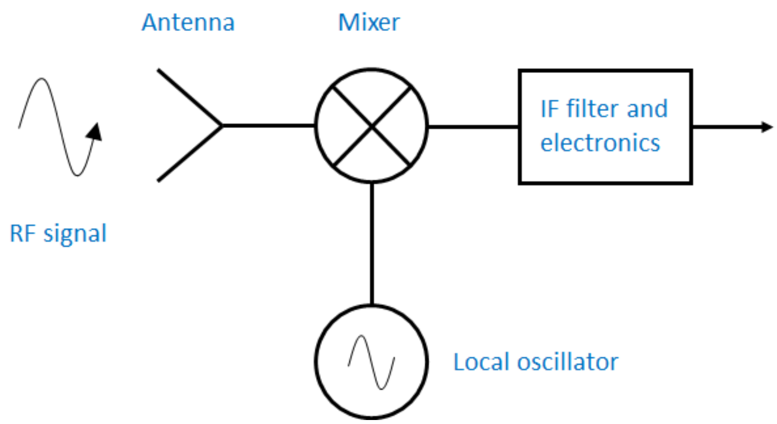


Fig. 2 Simple schematic presentation of a THz receiver front-end.

3. Modelling techniques

From the design perspective, the models can be divided to linear and nonlinear models. For a Schottky diode, the nonlinear part is the semiconductor-metal junction and the linear part contains everything else. The modelling approach discussed here follows the same logic: circuit simulator model for the nonlinear junction and electro-magnetic 3D simulator for the linear part.

3. A. Circuit simulator modelling

For circuit analysis, the model of the junction is typically a set of mathematical equations, including several parameters, such as series resistance, ideality factor, saturation current, and junction capacitance. If needed, this junction model is complemented with lumped capacitances and inductances, creating an equivalent circuit of the diode chip as illustrated in Fig. 3. The equivalent circuit can then be used in a circuit simulation with various other circuit elements in order to predict the performance of the component or device, such as a mixer or a multiplier.

3. B. Electro-magnetic modelling

At THz frequencies, where the chip size can be a significant portion of the wavelength, the equivalent circuit approach is susceptible to errors. Instead, a widely used approach in the diode modelling at THz frequencies is to use 3D electro-magnetic simulators to create a model of the mechanical structure of the diode.

When solved numerically, this model takes into account all the linear effects related to the physical structure of the diode. By importing the model into a circuit simulator and connecting it to the nonlinear junction model, the entire diode is modelled to a high degree of accuracy. The trick here is how to connect the junction "port" in the electro-magnetic simulator. One effective technique is illustrated in Fig. 4 and discussed in detail in [7, 9].

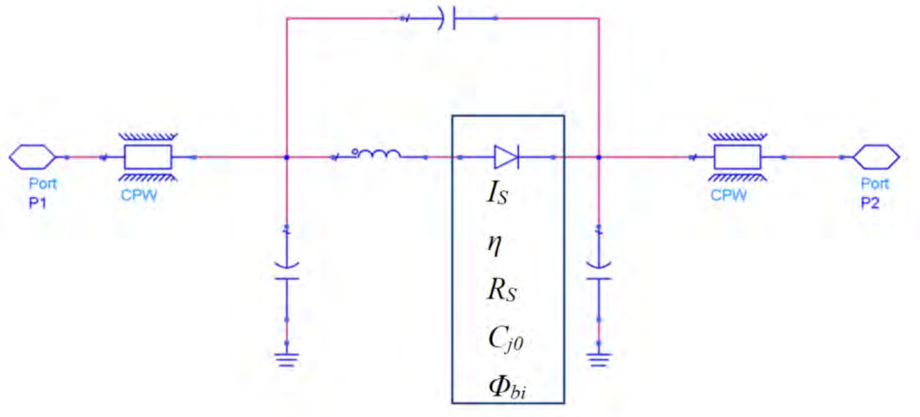


Fig. 3 Equivalent circuit for a Schottky diode connected to a coplanar waveguide transmission line.

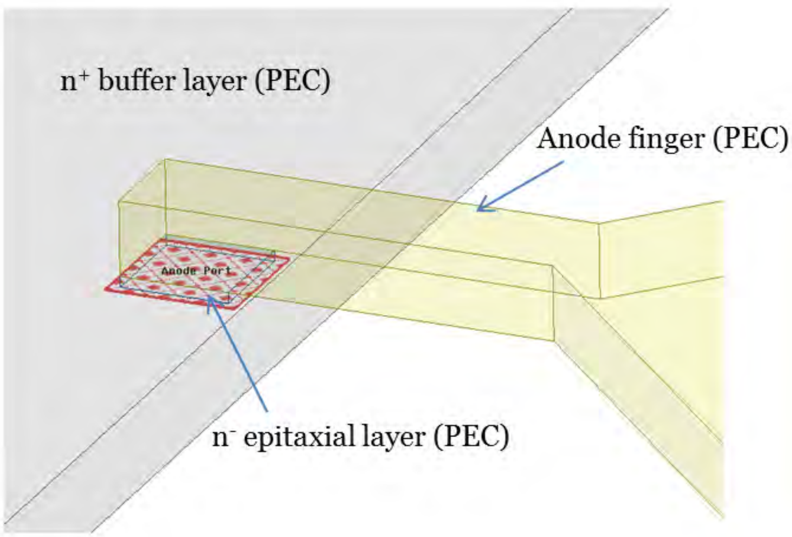


Fig. 4 Schottky port definition for connecting the physical junction model correctly. A GaAs epilayer is replaced by the coaxial port. This is where the circuit simulator junction model will be connected.

4. Characterization techniques

Characterization means measurement of relevant parameters of a device as a function of some incident signal, ambient condition, and/or time. The typical methods discussed here include current-voltage (I-V), capacitance-voltage (C-V) and S-parameter measurements. In addition, two somewhat less used methods, test jig measurements and thermal resistance measurements, are also addressed.

These methods provide information on the most crucial electrical and thermal parameters of the diode: the series resistance (R_S), ideality factor (η), saturation current (I_S), junction and parasitic capacitance (C_{j0}, C_p), finger inductance (L_f), barrier height (Φ_b), thermal resistance (R_θ), and thermal time constants (τ). Characterization methods provide these parameters for circuit models.

4. A. I-V Characterization

A simple measurement of current as a function of voltage (or vice versa) and the consequent fitting of Schottky diode I-V equation is an established and probably the most widely used method for determining I-V parameters, i.e., saturation current, ideality factor, and series resistance.

This approach is accurate and reliable for large lower frequency diodes and it is very useful also for THz Schottky diodes. However, when characterizing small, high frequency diodes, the effect of self-heating should be accounted for. The self-heating changes the values of ideality factor and saturation current and leads to too small an estimate for the series resistance. This effect is illustrated in Fig. 5 and discussed in detail in [10].

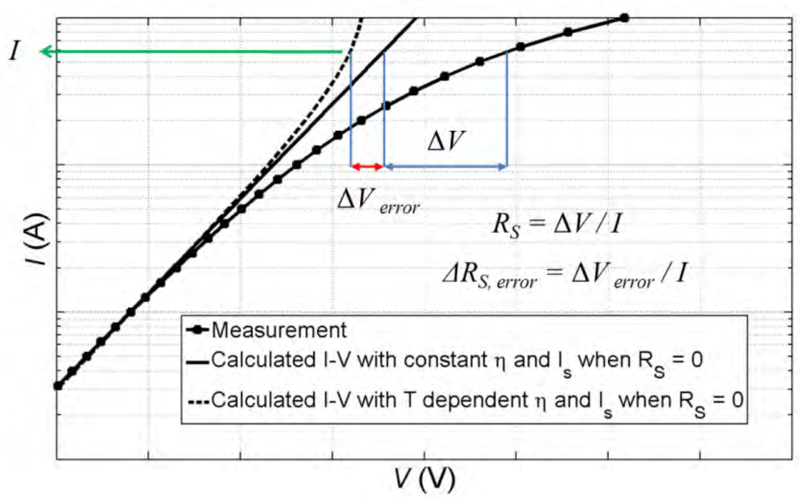


Fig. 5 Extraction of the series resistance and the error caused by the assumption that the saturation current and ideality factor have constant values in all bias points.

4. B. C-V Characterization

The total capacitance of a Schottky diode can be roughly divided into a nonlinear junction capacitance and constant parasitic capacitance. By measuring the capacitance as a function of voltage and fitting the results to the well-known Schottky diode C-V equation, the C-V parameters, i.e., junction and parasitic capacitance and Schottky barrier height can be extracted. This is illustrated in Fig. 6.

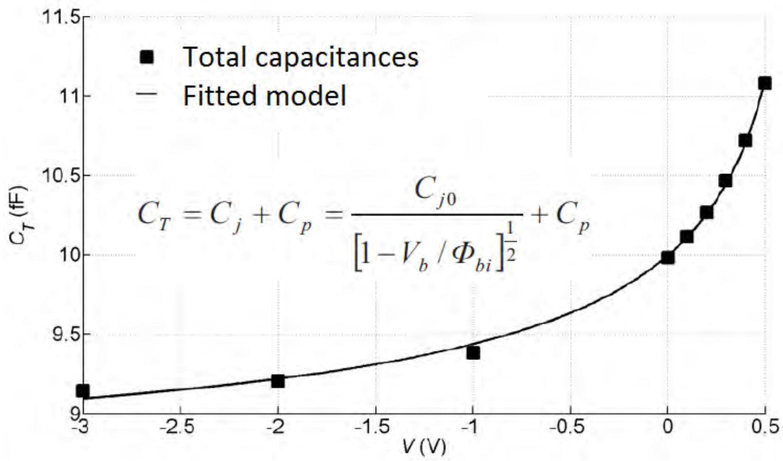


Fig. 6 Schottky C-V extraction. C-V equation is fitted to total capacitance values.

4.C. S-parameter Measurements

S-parameter measurements can be used to verify I-V and C-V measurement results. This is useful, as the measurement at high RF frequencies imitates the real operation environment of the diode more closely than DC or low-frequency measurement. High-frequency measurements may also give an indication on the value of the finger inductance of the diode, although this is a challenging task considering the small effect of the inductance below 100 *GHz*. Fig. 7 shows an example of a zero-biased S-parameter measurement of a Schottky diode on carrier (Fig. 1) compared to a circuit simulation of the equivalent circuit in Fig. 3 [7].

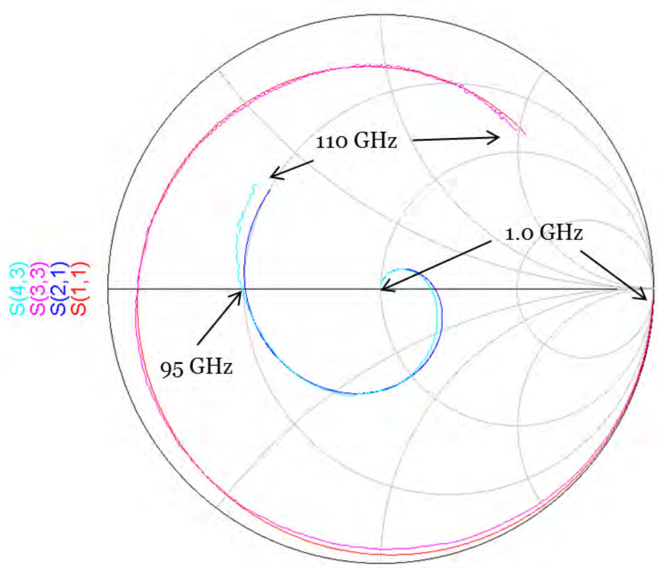


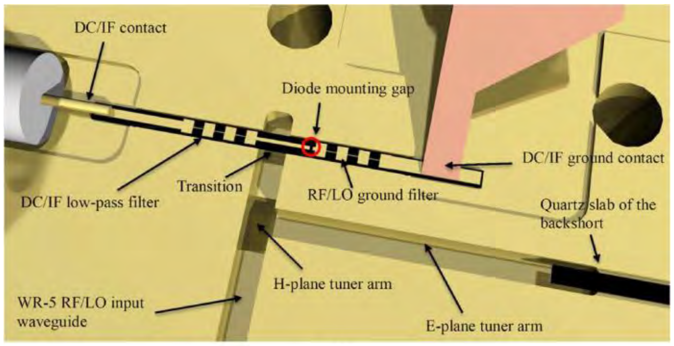
Fig. 7 S-parameter measurement for a diode on carrier (Fig. 1) and simulation result using equivalent circuit in Fig. 3 at 1-110 *GHz*. Diode is not biased (0 V). S(1,1) and S(2,1) are the reflection and transmission coefficients from the equivalent circuit simulation. S(3,3) and S(4,3) are measured reflection and transmission coefficients.

4. D. RF Characterization in a Test Jig

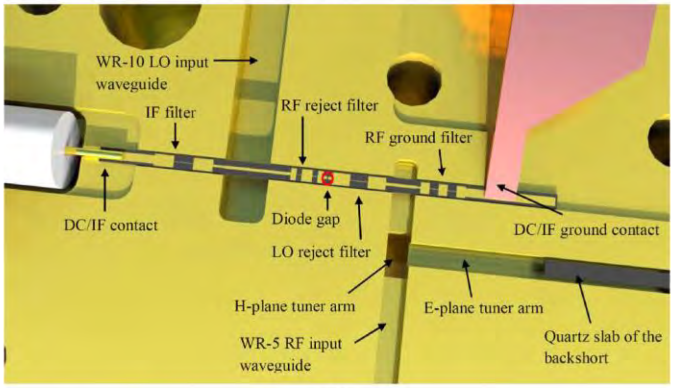
The most reliable way of testing a diode's performance in a mixer or a multiplier is to use it in a mixer or in a multiplier. However, this is often not a feasible solution, as fabrication, machining and assembling fixed-tuned waveguide blocks is a time and money consuming job.

A solution for this is to use a universal test jig, where any diode can be tested in its typical operation environment. The waveguide block needs to have low-loss, tunable impedance matching circuit in order to get the best performance out of different types of diodes. The changing of diodes or diodes mounted on carrier substrates should also be relatively simple.

In [11], such test jigs for single anode and antiparallel mixer diodes are designed, fabricated, and demonstrated. Fig. 8 shows lower (the block half with the carrier substrate) waveguide blocks for both test jigs. The impedance matching is implemented with low-loss waveguide impedance tuners utilizing dielectric-based waveguide backshorts.



(a)



(b)

Fig. 8 3-D illustrations of the lower waveguide blocks. (a) Fundamental mixer test jig. (b) Subharmonic mixer test jig .

4. E. Thermal Characterization

In addition to the electrical measurements, the diodes can be characterized thermally. Interesting thermal parameters are total thermal resistance, thermal time constants, thermal impedances and the maximum junction temperature. Thermal characterization is closely related to the reliability testing of diodes, in which the reliability and electrical behavior of the diodes are monitored under various electrical and thermal stress tests and as a function of time.

The available techniques for thermal characterization of small Schottky diode devices can be roughly divided into three categories. These are thermal modeling, imaging methods, and electrical test methods [12, 13]. In the case of small area Schottky diodes, the imaging methods cannot provide speed, resolution, or penetration of the anode metallization. Thermal modelling techniques, on the other hand, may or may not be very predictive, depending on the quality of the fabrication and assembly steps of the final device, and the fidelity of the model.

The transient thermal characterization method described in [13] is based on measurement of the transient cooling curve. Together with temperature dependent I-V measurements this cooling curve enables the extraction of thermal resistances and thermal time constants of a Schottky diode, and consequently, the maximum junction temperature. An example of the transient thermal characterization result is shown in Fig 9.

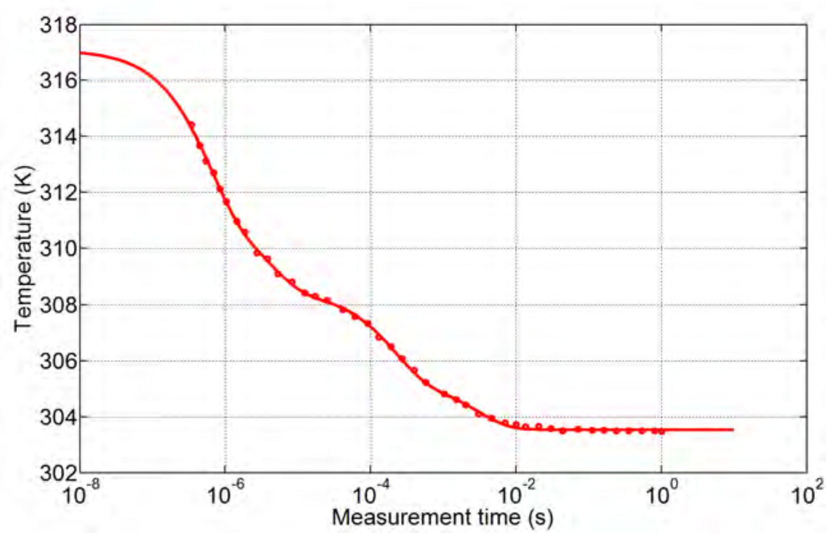


Fig. 9 Transient thermal characterization of a high-power Schottky diode multiplier. The red dots are the extracted junction temperature values as a function of time and the solid line is the fitted cooling curve with the assumption of exponential cooling behavior and four thermal time constants.

5. Conclusions

Various modelling and characterization methods for THz Schottky diodes have been presented. The methods provide designers accurate and reliable tools for designing and building Schottky-based components with state-of-the-art performance, while minimizing expensive trial-and-error rounds.

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