Characterisation of THz Schottky diodes for MetOp-SG instruments

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Abstract— **Schottky diode technology is used for frequency conversion and generation in three of the mm-wave and THz instruments on-board the European Space Agency's MetOp-SG satellites. The instruments are MWS (MicroWave Sounder), MWI (Microwave Imager) and ICI (Ice Cloud Imager). In order to ensure the storage and operational life time in addition to performance requirements, reliability assessment for the diodes is performed well before the fabrication of the instruments flight models. This paper presents the thermal characterisation of Schottky diodes used in the instruments as a part of reliability assessment process. Different multiplier and mixer prototype modules have been developed and thermally tested. In addition, thermal simulations are also carried out for comparison with the measurement results. Furthermore, thermal measurements on several identical multiplier blocks are also made that provides information on reproducibility of the assembly of discrete RF devices from the thermal perspective. Finally, some RF measurements are also carried out for comparison to the thermal impedance measurement results made on the same block and the same diodes.**

I. INTRODUCTION

Semiconductor technology trends toward smaller, faster and more powerful applications which have increased the importance of the thermal characterization of such devices. Smaller and more powerful are the requirements that imply more challenges in the thermal world. Smaller size means increased heat flux densities and therefore increased junction and die temperatures, leading to accelerated aging and thermally induced failures [1]-[3]. Thermal characterisation refers to the measurement of the temperature response of a device to the internal self-heating [4]. The fundamental principle is to determine the junction temperature of the device and then calculate the thermal resistance under known input power level. In general, a circuit can have several thermal resistances (or impedances) and thermal time constants and the junction temperature can be given as

$$T_J = T_0 + P_T R_\theta \,, \qquad (1)$$

where T_0 is the ambient temperature, P_T is the power dissipated in the junction and R_θ is the total thermal resistance, or often called only the thermal resistance.

Various thermal characterisation methods are available for evaluation of semiconductor devices [5]-[10] however, usability and accuracy of these methods depends on the measurement conditions and device under test (DUT). In this work, we characterise the developed prototypes based on the transient current measurement method [11]. However it is to be noted that here the measurements are made directly on the mixer and multiplier prototype blocks using a single SMA connector (for DC biasing) which is an added advantage of the measurement setup.

MetOp-SG is a joint EUMETSAT/ESA programme, which provides the next generation polar-orbiting meteorological satellites beyond the 2020 timeframe. Several microwave, millimeter and sub-millimeter wave instruments using Schottky technology are included in the MetOp-SG: MWS (MicroWave Sounder), MWI (Microwave Imager) and ICI (Ice Cloud Imager). All of these instruments include heterodyne receiver channels featuring Schottky diodes devices. The multipliers and mixers presented in this paper have been developed as a part of the prototype modules for these three instruments. They are representative of all the Schottky based components required to build 183, 243, 325, 448 and 664 GHz channels for ICI, and additionally the 166 and 229 GHz channels for MWI and MWS instruments on-board MetOp-SG. To build all these multipliers and mixers, different substrate types are required, high thermal dissipation and low losses, as well as different diodes (varactor and varistor) from European diode manufacturers (ACST in Germany [12] and Teratech in the UK [13]).

Thermal impedance measurement as well as thermal simulation is extremely important to determine the life time testing conditions of these devices, and to evaluate their reliability for space operational missions such as MetOp-SG. This reliability assessment includes thermal characterisation of the diodes which has two goals: first, the determination of the maximum temperature during normal operation conditions and second, the verification of the sufficient heat flow path in order to keep the diodes in the wanted temperature range throughout the mission. Moreover, with the ability to make measurement of real RF blocks, we can directly compare the thermal impedance measurement results with RF results performed on the same block and the same diodes. In addition, information on repeatability (in terms of thermal aspect) of the assembly of discrete devices can also be obtained.

II. MEASUREMENT SYSTEM

Measurement setup for the thermal characterisation of prototype blocks consists of a semiconductor parameter analyser, a heating oven and a temperature sensor as shown in Fig. 1. One port DC-IV measurements are performed in the temperature range of 303 K to 353 K with the step of 5 K and the transient current measurements are carried out at 303 K. All the thermal measurement results presented in this paper are performed at this temperature. In this work, we are using one channel (see Fig. 1) of the semiconductor parameter analyser for I-V characteristics and transient current measurements. This is a very important advantage of the measurement system because complete I-V and thermal properties of the mixer and multiplier blocks can be obtained by measuring from only one port (DC bias port) of the prototype block. This implies that we do not need to mount the diodes to separate module blocks for characterization purpose.

The parameter analyser is connected to the Remote–sense and Switch Unit (RSU), where the current/voltage measurement is carried out. The force voltage is supplied from one channel of the analyser and the current measurement is performed in RSU of the same channel.

Temperature dependent DC I-V measurements are required to generate a current-temperature (I-T) relationship, also known as calibration curve. I-T calibration must be performed at low power level which can be obtained with appropriate selection of the measurement current level. For this work, we use 200 µA as the measurement current level (negligible self-heating effect). For transient current measurement, the DUT is heated for pre-defined time duration with a heating current (9 mA) which is then abruptly switched to a lower current level, also known as measurement current level. This current transition is measured as the DUT cools down. The corresponding temperature response of the device is then obtained from the I-T calibration curve. Finally the thermal parameters are extracted by an exponential least square curve fitting method with (2) [11].

$$T(t) = T_0 + T_1 \times \left(\exp\left(\frac{-t}{\tau_1}\right)\right) + \cdots + T_n \times \left(\exp\left(\frac{-t}{\tau_n}\right)\right) \quad (2)$$

where, $$\tau_n = R_{\theta,n} C_{\theta,n} \quad (3)$$

T_n (n > 0) is the level of temperature change related to a thermal resistance of a certain part of the device and τ_n is the corresponding thermal time constant. $R_{\theta,n}$ is the thermal resistance associated to this part of the device, and $C_{\theta,n}$ is the corresponding thermal capacitance.

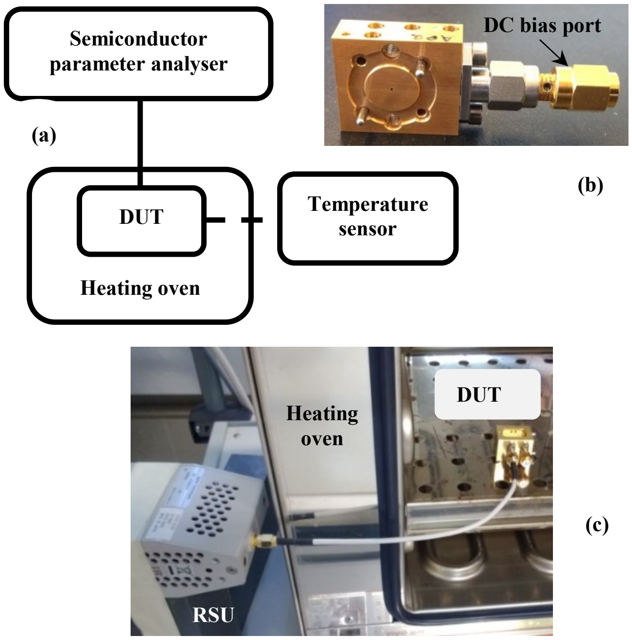

Fig. 1 (a) Block diagram of the measurement setup, (b) photograph of the prototype blocks under test and (c) photograph of the prototype block (inside the oven) connected to the Remote-sense and switch unit (RSU) of the semiconductor parameter analyser.

III. MULTIPLIER AND MIXER BLOCKS UNDER TEST

Five multiplier blocks and two mixer blocks from RPG Gmbh, Germany are tested in this work. The multiplier block M01 is a W-band tripler operating between 80 and 92 GHz, featuring a GaAs Schottky discrete varactor chip from Teratech with 6 anodes in series. Details about the circuit can be found in [14]. The M02 multiplier block is equivalent to M01 but features a 4-anodes ACST discrete chip instead. The block M03 is a high power 112 GHz doubler using a 4-anodes ACST discrete GaAs varactor chip. M06 is a medium power 160-170 GHz doubler using a 4-anodes GaAs Schottky discrete varactor chip from Teratech. M07 is a high power equivalent to M06, featuring a 4-anodes GaAs Schottky discrete varactor chip from ACST. All M01 to M07 blocks use a high thermal conductivity substrate in order to heat sink the diodes as good as possible.

The Mixer block M17b-1 is a 448 GHz sub-harmonic mixer featuring an anti-parallel pair of planar Schottky diodes from Teratech. The Mixer block M17b-2 is a 448 GHz sub-harmonic mixer featuring an anti-parallel pair of planar Schottky diodes from ACST.

IV. MEASUREMENT RESULTS

A. Thermal Measurements

All the prototype blocks are characterized thermally using the transient current measurement method. The thermal response of each block is fitted with the exponential equation to extract the thermal parameters such as thermal resistance and maximum operating temperature. In this section, we present thermal response and extracted thermal parameters (see Table I) of the blocks under test. Fig. 2 (a) show the temperature response of tripler blocks M01 measured from each port. M01 tripler consist of six anodes in series. Measurement from port 1 biases three anodes and that from port 2 biases other three in series respectively. Measurements are made from both the port of the tripler. Fig. 2 (b) presents the temperature response of M03 doubler block and Fig. 2 (c) shows the measurement results for mixer blocks (M17b-1 and

M17b-2). The time axis is presented in log-scale to better demonstrate the dynamic thermal response of the DUT. The flow of heat from the diode junction to the local ambient through various thermal stages is exhibited by the plateaus in the measured result and is characterized by several thermal time constants (Table I).

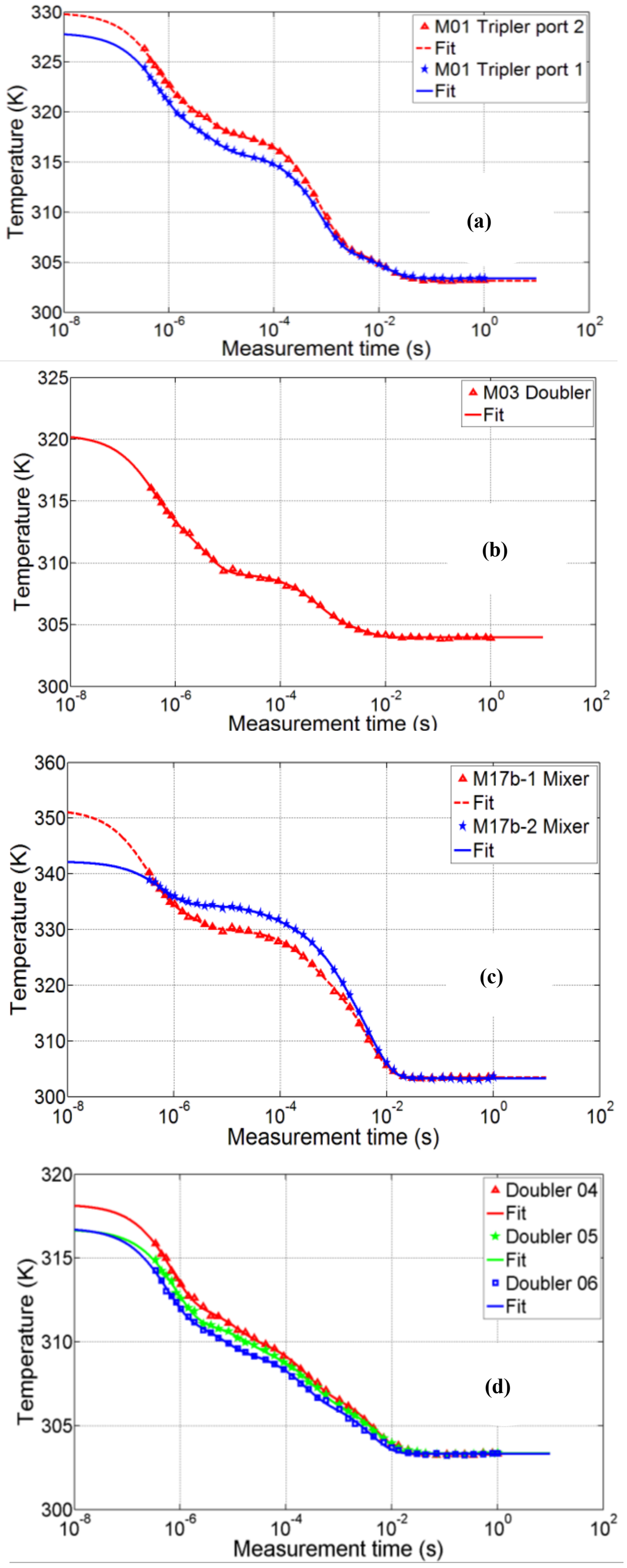

Fig. 2. Measured thermal response of the prototype blocks (a) M01, (b) M03, (c) M17b-1 and M17b-2 mixers and, (d) thermal response for three identical M07 doubler blocks (04, 05 and 06).

Thermal measurements can be used as a tool to check the reproducibility of the discrete RF devices. For this purpose, three identical multiplier (M07 doubler) blocks with same diode types are tested thermally. Here, M07 is a high power 160-170 GHz doubler using a 4-anodes GaAs Schottky discrete varactor chip from ACST. Fig. 2 (d) shows the temperature response of these blocks where block 04 seems to have slightly higher thermal resistance and peak operation temperature compared to block 05 and 06 (see Table I). Some small differences in performance may arise from the mechanical tolerance and mounting uncertainty but from these thermal tests, it is observed that our thermal characterization technique can be a good tool to check the reproducibility of the discrete devices.

B. RF Measurements

In addition to the thermal measurements, RF tests are also performed for three identical multiplier (M07-04, 05 and 06) blocks. Fig. 3 presents the RF results with input power, output power and efficiency in the same plot. Comparing the thermal and RF results for these three blocks it is observed that the block with larger thermal resistance (or peak temperature) has smaller output power as well as lower efficiency (from Fig 2 (d) and Fig 3). In addition, the block with higher leakage current also has larger thermal resistance and smaller output power and efficiency.

V. SIMULATION RESULTS AND COMPARISON

Steady state thermal models have been calculated using ANSYS Workbench 14.5. For all calculations a constant heat flux was applied to the diode anodes. The substrates are thermally connected to a block and the temperature is kept constant at 298 K. Convective cooling and radiation has been neglected. After charging up the thermal capacities of the system, the temperature distribution becomes stationary and the thermal equilibrium is reached.

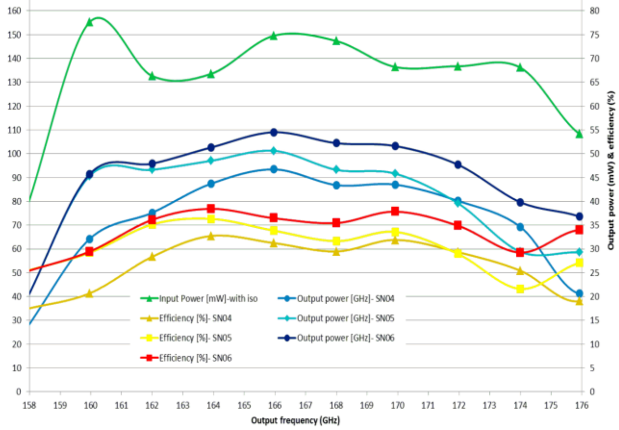

Fig. 3. RF measurement results showing input power, output power and efficiency for three identical M07 doubler blocks.

TABLE I
EXTRACTED THERMAL PARAMETERS OF MULTIPLIERS AND MIXER BLOCKS

Prototype	Peak temp. (K)	Ambient temp. T_0 (K)	Time constants (s)				Power, P_T (mW)	Total thermal resistance, R_0 (K/W)
			τ_1	τ_2	τ_3	τ_4		
M01 port 1	328	303.4	$5.8\bullet10^{-7}$	$5.9\bullet10^{-6}$	$7.4\bullet10^{-4}$	0.013	21.4	1140
M01 port 2	330	303.1	$5.9\bullet10^{-7}$	$5.6\bullet10^{-6}$	$7.5\bullet10^{-4}$	0.013	21.4	1250
M02 port 1	323	303.4	$6.5\bullet10^{-7}$	$6.1\bullet10^{-6}$	$2.1\bullet10^{-4}$	0.009	17.1	1170
M02 port 2	325	303.8	$6.1\bullet10^{-7}$	$3.8\bullet10^{-6}$	$1.8\bullet10^{-4}$	0.009	17.1	1260
M03	320	303.9	$5.1\bullet10^{-7}$	$6.1\bullet10^{-6}$	$1.9\bullet10^{-4}$	0.002	13.9	1170
M06	321	303.8	$5.6\bullet10^{-7}$	$4.7\bullet10^{-6}$	$4.4\bullet10^{-4}$	0.002	16.5	1060
M17b-1	351	302.8	$2.9\bullet10^{-7}$	$2.1\bullet10^{-6}$	$3.9\bullet10^{-4}$	0.004	3.8	12800
M17b-2	342	303.3	$6.1\bullet10^{-7}$	$6.5\bullet10^{-6}$	$7.3\bullet10^{-4}$	0.005	4.4	8740
M07-04	318	303.3	$6.7\bullet10^{-7}$	$1.1\bullet10^{-5}$	$2.4\bullet10^{-4}$	0.005	12.6	1170
M07-05	316	303.3	$7.9\bullet10^{-7}$	$1.7\bullet10^{-5}$	$2.8\bullet10^{-4}$	0.005	12.6	1060
M07-06	316	303.3	$5.2\bullet10^{-7}$	$6.1\bullet10^{-6}$	$2.1\bullet10^{-4}$	0.004	12.6	1060

Since the thermal resistance is a material property, the steady state temperature of the diodes varies on different substrates and for different epi and buffer layer combinations.

The maximum temperature of the diodes along with the power dissipation per anode in simulation is shown in Table II. The measured thermal resistance of each block and the corresponding estimated anode temperature are also given for comparison purpose. For block M01 and M02, two values of thermal resistance are reported which are obtained by measurements from each port as explained earlier in the text.

It is evident from Table II that the simulated anode temperatures are in good agreement with the values obtained from measurement. The discrepancy between the simulation and measurement results might be explained by the fact that in thermal simulation, it is difficult to know the exact anode diameter, which significantly affects the hot spot temperature. The geometry of the diode is only an approximate in the model compared to reality. Hence, the simulation results might not be as accurate as the real measurements.

VI. CONCLUSION

Thermal characterisation is an important part of the reliability tests of semiconductor devices. This is especially the case in applications which have to operate a long period of time without the possibility of repair or replacement, such as satellite instruments. Thermal characterisation method for special case of THz Schottky diodes used in MetOp-SG satellite mission instruments is discussed. Measurement results for different multiplier and mixer block prototypes are reported and a comparison to the results from thermal simulations of the multiplier blocks is also included. Thermal as well as RF tests are also presented for three samples of a doubler block with same diode. Thermal characterization method used in these test is found to be a good tool for reproducibility check for assembly of discrete devices. Furthermore, some interrelation between thermal and RF measurement results are also observed and may be further studied as a field of investigation.

TABLE II
COMPARISON OF THE SIMULATED AND MEASURED ANODE TEMPERATURE

Prototype	Power / Anode, Simulated (mW)	Anode temperature, T_j, Simulated (K)	Anode temperature, T_j, Estimated (K)
M01 port 1/port 2	15	354	347/354
M02 port 1/port 2	23	351	352/356
M03	30	422	438
M06	13	347	353
M07	30	422	396

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