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Thermal conductivity of silver loaded conductive epoxy from cryogenic to ambient temperature and its application for precision cryogenic noise measurements

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ABSTRACT

The pressure to increase the sensitivity of instrumentation has pushed the use of cryogenic Low Noise Amplifier (LNA) technology into a growing number of fields. These areas range from radio astronomy and deep space communications to fundamental physics. In this context manufacturing for cryogenic environments requires a proper thermal knowledge of the materials to be able to achieve adequate design behavior. In this work, we present experimental measurements of the thermal conductivity of a silver filled conductive epoxy (EPO-TEK H20E) which is widely used in cryogenic electronics applications. The characterization has been made using a sample preparation which mimics the practical use of this adhesive in the fabrication of cryogenic devices. We apply the data obtained to a detailed analysis of the effects of the conductive epoxy in a monolithic thermal noise source used for high accuracy cryogenic microwave noise measurements. In this application the epoxy plays a fundamental role since its limited thermal conductivity allows heating the chip with relatively low power. To our knowledge, the cryogenic thermal conductivity data of this epoxy has not been reported before in the literature in the 4–300 K temperature range. A second non-conductive epoxy (Gray Scotch-Weld 2216 B/A), also widely used in cryogenic applications, has been measured in order to validate the method by comparing with previous published data.

1. Introduction

Certain applications such as radio astronomy and deep space communications require state of the art low noise performance. At microwave frequencies this is usually achieved by using Low Noise Amplifiers (LNAs) with InP or GaAs High Electron Mobility Transistors (HEMTs) cooled at cryogenic temperatures [1,2]. One of the main difficulties found in the evaluation of these devices is to obtain accurate noise temperature measurements, since the errors of commercially available instruments and noise sources typically exceed the value to be measured by an order of magnitude. One possible way to circumvent this problem is to use an improved noise source consisting of a microwave termination (50 Ω resistor) at a well known and controlled cryogenic temperature directly connected to the input of the Device Under Test (DUT). Since the output noise of the resistor is almost purely thermal [3], the equivalent noise temperature of the DUT can be obtained by taking total output noise power measurements at least at two different physical temperatures of the input termination [4]. A device specially conceived to perform this type of measurements, with a microwave termination, a heating resistor and a temperature sensor all integrated in the same semiconductor GaAs chip has been designed [5] and characterized [6]. For this application the noise source chip is mounted into a specially designed metallic chassis with DC and microwave connectors to allow easy manipulation. The monolithic GaAs chip is attached to the chassis using

Abbreviations: LNA, Low Noise Amplifier; HEMT, High Electron Mobility Transistor; DUT, Device Under Test; FEM, Finite Element Model; OFHC, Oxygen Free High Conductivity.

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EPO-TEK H20E silver filled conductive epoxy [7]. For a correct operation, this device requires a good electrical contact between the back side of the chip and the chassis and, in the ideal situation, a poor thermal conductivity of the epoxy relative to GaAs. This would ensure that the power dissipated at the surface of the chip produces a temperature gradient confined to the epoxy layer outside semiconductor, leaving the chip, and therefore the microwave termination and sensor, almost isothermal. The aim of this work is to determine whether the thermal conductivity difference between the semiconductor and the epoxy is high enough to ensure a situation close to the ideal. Also, a low thermal conductivity of the epoxy ensures that an acceptable temperature increment could be obtained at the microwave termination and sensor without requiring the dissipation of a large amount of power. To evaluate the deviation from the previously described ideal situation a Finite Element Model (FEM) of the noise source has been developed. Using this model the temperature difference between the microwave termination and the sensor has been estimated to be of the order of tenths of a Kelvin under typical working conditions. In addition, average temperatures in the region of the chip where the sensor is located have been compared with experimental data from a real working noise source obtaining good results. Also, the FEM simulation has been used to determine the contribution of the different materials to the temperature gradient of the noise source, revealing a very low contribution of the GaAs layer and a higher than initially expected contribution of the chassis.

The thermal conductivity is measured using the longitudinal steady heat flow method [8]. In our version of this method, measurements of the temperature gradient are taken of a thin sample of the material while heating power is applied on one side keeping the other at a constant temperature. Blocks of gold plated OFHC Cu have been used to attach the required hardware at both sides of the epoxy layer ensuring that the temperature gradient is confined to the sample. The experimental setup has been validated by measuring a non-conductive epoxy [9] and contrasting the results with those in the literature [10]. Thermal boundary resistance contributions have not been corrected for two reasons: (a) previous studies prove that their contribution is low in comparison to thermal resistance of the epoxy layer [10]; and (b) the fact that this contribution would also be present in any practical application of the material.

1.1. Noise source description

The device to be analyzed is the noise source chip depicted in Fig. 1 [5], which was conceived for accurate cryogenic Low Noise Amplifier (LNA) characterization. The chip integrates on the surface of a single $1.00 \times 1.00 \times 0.05\ \text{mm}^3$ GaAs chip, the three elements required in a variable temperature load: (a) a temperature stable broadband 50 Ω microwave termination used as a thermal noise generator; (b) a heating resistor required to modify the chip temperature; and (c) a temperature dependent resistor based on transistor gate technology used as a sensor for temperature measurements.

The chip is attached to a $23.4 \times 19.5 \times 8.2\ \text{mm}^3$ gold plated brass chassis using an approximately 10 µm thick conductive epoxy layer. The chassis also holds additional substrates for routing the microwave termination, heating resistor and 4 wire temperature sensor to their corresponding external connectors. Electrical connections between these substrates and the chip are made using 17.5 µm diameter bonding wire. When in use, the source is thermally connected to the cold plate of the cryostat using a high conductivity tin platted copper braid. Under typical operating conditions of a base temperature of about 15 K and a dissipated power of 0.4 W, the microwave termination experiences a temperature increment of about 25 K (hot temperature of about 40 K). The key advantages of this system as a noise source are the good frequency response of the microwave termination and its reduced dimensions which translate in a low thermal heat capacity and consequently a fast time response [6].

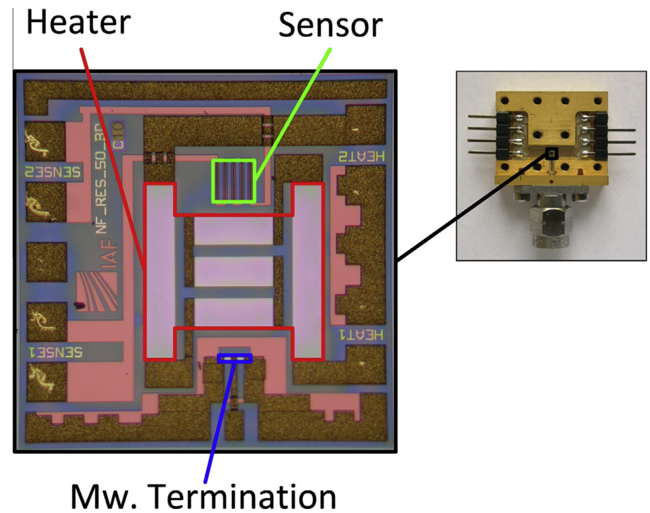

Fig. 1. Noise source module without its lid and detail of the chip with microwave termination, heater and temperature sensor outlined.

Regarding the accuracy of this system, the effective output noise temperature should be corrected to account for the electrical loss of the transmission lines connecting the chip to the Device Under Test (DUT). The on-chip coplanar line has a negligible contribution since it is practically at the same temperature as the microwave termination as it will be shown in Section 2.2. The contribution of microstrip external line can be estimated for the worst case scenario of a 50 GHz frequency and temperature equal to the base temperature. Under these circumstances and for a base temperature of 15 K and a dissipated power of 0.4 W the noise temperature at the end of the microstrip line would be ~0.22 K lower than expected. If this correction is not taken into account the maximum error in the effective output noise temperature would be approximately 0.55%.

1.2. Thermal conductivity measurement setup

The experimental setup that has been used to determine thermal conductivity is based on the longitudinal steady heat flow method [8,11]. The one dimension Fourier law states that a heating power applied to the end of a sample, once thermal equilibrium is established, will produce a temperature difference along the direction of propagation of the heat flux, such that

$$P = -kA\frac{\partial T}{\partial x} \tag{1}$$

where P is the heat flux (W), A is the cross section (m^2), T is the temperature of the sample (K) and k its temperature dependant thermal conductivity. For a constant cross section, Eq. (1) adopts the integrated form

$$P = -\frac{A}{L}\int_{T_1}^{T_2} k(T)dT \tag{2}$$

where T_1 and T_2 are the temperatures at any two points along the path of the heat flow separated by a distance L (m). Following reasoning in [10], average thermal conductivity k_{av} between T_1 and T_2 can be defined as

$$k_{av} = \frac{1}{(T_2 - T_1)}\int_{T_1}^{T_2} k(T)dT \tag{3}$$