Faults Detection in the Heatsinks Mounted on Power Electronic Transistors

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***Abstract*—Nowadays, power electronics is widely used in many applications, e.g., in industrial field, transport field and household appliances used daily. Considering the high temperature reached in power circuits, it is necessary to introduce some heat dissipation systems able to transfer heat to the surrounding environment. The correct mounting of the heatsink or its physical deterioration over time can affect the operation of the system. The overheating may lead to an ageing acceleration of the power devices or to their permanent damage. This greatly influences the reliability and safety of power systems used in safety-critical applications, e.g., for automotive, rail or industrial environments. Hence, it is necessary to introduce some test strategies to identify those heatsinks that do not operate correctly, e.g., because they are not correctly assembled during the production of the Printed Circuit Board (PCB). This paper proposes a methodology to test the assembly of heatsinks on power devices. The proposed approach relies on an in-circuit test method at the end-production on the final PCB. The test is carried out without resorting to thermal measurements. Generally, the thermal measurements cannot be performed by the modern Automatic Test Equipment (ATE). The proposed test methodology was evaluated experimentally on a power MOSFET in TO220 package; the MOSFET considered is used in a half bridge.**

***Index Terms*—Power electronics, Heatsink test, Safety-Critical applications, End-manufactory in-circuit test**

I. Introduction

Power electronics plays a key role in modern technology. It is used in many industrial applications, in the transport and generation of electricity, in the transport systems of goods and people and in many everyday applications. Power electronics is involved in many safety-critical environments such as those industrial, automotive, medical and household ones. In safety-critical systems, a fault can lead to considerable consequences for the health or life of the users. Safety-critical systems require accurate test mechanisms at the end of their manufacturing and in field. All the aspects of critical systems must be tested: the digital control part, the analog part and the power part. Several software and hardware approaches are available to test the digital parts [1]. Other test strategies are also available to test the analog and power parts [2], [3] and to evaluate the fault coverage [4]–[7] of the test procedures. In contrast to the low power used in digital electronics, in high power applications the temperature can reach very high values [8]. For this reason, it is common to mount on the power devices some heatsinks for quick heat dissipation. Malfunctions of dissipating systems may lead to a dangerous overheating of the power devices. Even the dissipation systems, regardless of its complexity, may thus require testing strategies in order to verify their correct functioning at the end of the production process [9]. Unfortunately, the test of such systems is not always adequately considered and no specific test is carried out. Typically, passive dissipation systems are made of bulky heatsinks equipped with radial metal plates designed for heat dispersion. These systems may not work properly due to their incorrect assembly, their physical breakage or because they are obstructed with dust or dirt.

The aim of this paper is to propose an end-of-manufactory test strategy able to check the correct behavior of the dissipation systems. Currently, the check on the correct assembling of the heatsinks is often performed only in a qualitative way through a simple automatic optical inspection [10]. This test methodology is not sufficient to detect defects in the heatsink assembly phase; the optical inspection only provides a check on the presence of the heatsink on the final PCB. The goal is to propose a methodology able to detect the possible defects affecting the dissipation systems by means of electrical measurements. These defects may be related to the mounting phase of the heatsink during the assembly of the Printed Circuit Board (PCB) [11], [12], or to a damaged heatsink. The use of thermal probes on the heatsink under test is not always effective, because the temperature of the heatsink is not uniform over its surface and it is not always possible to identify a good point for measuring the temperature. Besides that, a lot of Automatic Test Equipment (ATE) are not equipped with thermal probes or other sensors able to monitor the temperature. Some power modules are equipped with thermal sensors suitable to detect the effectiveness of the heatsink. Furthermore, these sensors are rarely placed near all heatsinks present in the system. Usually, on-board sensors are used for monitoring the average temperature of the system. It is common to introduce simple thermal protections, such as those based on Positive or Negative Temperature Coefficient resistors (PTCs or NTCs), which turn off the system in case of

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excessive overheating [13]. Therefore, it is preferable to perform the heatsink test without executing direct thermal measurements, but exploiting voltage and/or current measurement on the Device Under Test (DUT). The modern ATE systems are equipped with several active and passive probes able to perform the electrical measurements with an excellent resolution. Obviously, this is possible only if the ATE is able to access the power devices pins (in other words, if a physical contact of the power device by the ATE probes is possible). In this paper, we propose an analysis of the impact of different assembling defects of the heatsinks on the electrical parameters of the transistor; in particular, the resistance between the drain and source terminals (Ron) of the MOSFET device is considered [14]. The R_{on} evaluation is used, in the proposed approach, for testing the heatsink assembly. Such test is performed in-circuit using an ATE. Considering a typical probe equipment of a modern ATE, the proposed methodology does not consider temperature measurements to perform the tests, but it uses only some electrical voltage measurements that can be easily and quickly performed by an ATE. The test is executed on the final PCB at the end of production. The test requires knowing the mathematical relationship between the junction temperature (T_j) and the R_{on} values, and this relationship is obtained experimentally by characterizing the transistor. In particular, the capability of the method to identify small variations of the thermal resistance is checked refering to a simple configuration.

This paper is organized as follows: Section II introduces some concepts concerning the modelling of thermal systems that are normally used to identify the suitable heatsink during the design of the system. In Section II the thermal effects on power devices are discussed. Section III introduces the concepts of thermal faults. The power case study used in this paper is described in Section IV. Section V reports the experimental results on the case study, while Section VI draws some conclusions.

II. Background

This section provides the reader with the required information about the thermal system [15], with particular emphasis on the physical meaning of the thermal quantities used in this paper. The second subsection describes the effects of the temperature on the power devices. Finally, the in-circuit test method developed in this work is described.

A. Thermal Concept in the Electrical Field

The main concept of the thermal system is briefly introduced. The heat flow propagation in a real device can take place in three different ways: convection, radiation, and conduction [16]. In electronic PCBs, the heat propagation occurs mainly due to the conduction phenomenon; convection and radiation phenomenons are normally not considered in the electronic field [16]. Thermal systems are modelled referring to equivalent circuits composed of thermal resistances and thermal capacitances [16], [17]. In physics, the thermal resistance is defined as the difficulty that heat encounters when going through a solid element of the system [17]. With reference to Fig. 1, that shows a typical heatsink used on a power transistor encapsulated in the TO220 package, it is possible to identify three thermal resistances (R_{thjc}, R_{thcd}, R_{thda}). The thermal resistance R_{thjc} identifies the difficulty to propagate the heat through the transistor (i.e., from the die to the surface of the transistor package). The value of the R_{thjc} is provided by the transistor manufacturer. The heat propagation difficulty between two contact surfaces is modelled by R_{thcd} resistor; the value of R_{thcd} depends on how the heatsink is mounted on the transistor, as discussed in [18] and [19]. The value of such resistance is mainly determined by the size of the surface contact and by its quality. Finally, R_{thda} describes the thermal resistance between the heatsink and the air. For the sake of simplicity, in this work, the equivalent thermal resistance from the junction to ambient is considered (R_{thja}).

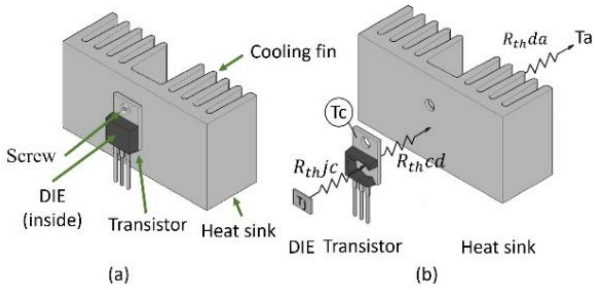

Fig. 1. Model approximation of thermal system: a) Physical system and b) physical system with thermal resistance [20].

The description provided in Fig. 1 is a model approximation, because there are a lot of other factors that influence the system. Fig. 1 assumes that the heat flow is unidirectional from the die to the heatsink, but the heat propagates in every direction. Moreover, the ambient temperature (T_a) or other heat sources near to the transistor, influence the system dissipation. For these reasons, the development of a thermal model starting from a simple physical analysis of the system is difficult. In general, as discussed in [21], the R_{thja} can be estimated by

$$R_{thja} = \frac{T_j - T_a}{P_{dis}} \tag{1}$$

where R_{thja} identifies the whole thermal resistance of the system, T_j the junction temperature of the transistor, T_a the ambient temperature, and finally P_{dis} is the power dissipated by the transistor.

In addition to thermal resistances, thermal capacitances should be also taken into account. The thermal capacitance of an object describes the amount of heat that the object can store. Such capacitance is defined as the amount of heat to be supplied to a given mass of a material to produce a unit change in its temperature [17]. The thermal capacitance is determined by the mass (M) of the object and by its specific heat (C):

$$C_{th} = CM \tag{2}$$

The thermal capacitance influences the duration of the thermal transients. When the physical system is in steady-state, i.e. the power dissipated by the transistor is constant, the thermal capacitances do not influence the temperature trend.

B. Thermal Effects on Power Devices

The junction temperature significantly impacts the performance and the reliability of the transistors. A high junction temperature accelerates the failure mechanisms and reduces the lifetime of the devices. From an electrical point of view, these failure mechanisms [17] include the gate oxide breakdown, the electromigration, the hot electron effects, and the negative bias temperature instability. The causes of device break are not limited to electrical issues, but also to physical and mechanical ones [17]. The junction temperature fluctuations create, inside of the power devices, some mechanical stresses [17]. The transistor is composed of materials with different thermal coefficients of expansion. The temperature variation causes mechanical stresses between the different materials (silicon, aluminium, iron, plastic, and so on) [17]. The mechanical stresses are the main causes of break of the solder connection of the devices on the board. Other important issues connected to the mechanical stresses are related to the wire bonding connections between the die and the external contacts of the devices. All these aspects reduce the reliability of the device in the long term: this is one of the key aspects for safety systems. Moreover, the junction temperature increase influences many of the functional parameters of the power devices [13], [17], [21]. The drain-source resistance of the MOSFET increases with the junction temperature increase [17], [21], [22]. The conduction loss is almost doubled when the temperature increases from 25 ℃ to 150 ℃ [16], [17]. On the other hand, the threshold voltage of a MOSFET decreases with the temperature increase [17], [21]. The reduction in the threshold voltage increases the leakage current of the transistor [17], [21]. All these features of the transistors can be used as Thermal Sensitive Parameters (TSEP) [23]. Such parameters, along with a proper calibration process, allow one to evaluate the junction temperature. In this work the R_{on} is considered as TSEP.

C. In-Circuit Test Method

Modern automatic test equipment (ATE) allow one to perform different tests to be performed at the end of production, and these tests are based on the in-circuit test method. The ATEs are equipped with a given number of needles able of contacting the electrical components on the PCB. These electric needles can be used to apply voltages or to inject/sink currents in the circuit. Moreover, with electric probes, it is possible to perform voltage or current measurements. In general, current measurements are only possible if sense resistors are present in the circuit. During the in-circuit test, the board is not powered and no electrical stimulation is applied to the system, except those supplied by the ATE. Clearly, all precautions concerning the positioning of the guarding probes [11], [12] must be considered. Guarding probes are able to avoid damage during the in-circuit test, as widely discussed in [11][12]. The test electrical stimuli are applied directly to the transistor. The stimuli would spread through the network damaging the electrical circuits in absence of the guard probes. These guarding probes are useful in the points connected to ground for escaping portions of circuits during in-circuit tests. The current ATEs are equipped with numerous guarding probes used during the in-circuit tests.

III. Proposed Approach

In this paper, a *thermal fault* is defined as an alteration of the dissipation capability of a heatsink, in accord with the thermal resistance concept described in Section II. A thermal fault is an increase of R_{thja} over the expected value. In other words, there is a further obstacle to the passage of heat from the die to the air due to a thermal fault. Typically, a thermal fault can be caused by incorrect assembling of the heatsink or its physical damage. The proposed approach is based on a characterization of the transistor, and this characterization is performed before the test phase. In particular, R_{on} of the transistor is characterized considering different T_j. Afterwards, this characterization is used in the test phase.

A. Mosfet Temperature Characterization as R_{on} Function

The evaluation of the MOSFET temperature performing electrical measurements requires an initial calibration procedure. In particular, a constant current is forced for increase the T_j temperature; The drain source voltage V_{ds} is measured during the variation of the T_j. Such characterization can be divided in two steps, a heating phase and a cooling one. During the heating phase the transistor is in the saturation region, in order to dissipate a lot of power for quickly reach a high temperature (about the maximum T_j supported by the device). Instead, during the cooling phase the transistor is switched in ohmic region with the purpose of dissipating less power. The temperature of the device is monitored, and synchronously, only during the cooling phase, the V_{ds} voltage is acquired. Such characterization is performed by means of the circuit in Fig. 2.

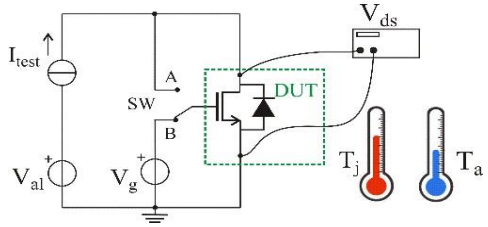

Fig. 2. Circuit for extrapolating the relation between T_j and R_{on}.

The switch SW allows the user to move from the diode configuration of the MOSFET to the ohmic region. The transistor is in saturation region when configured as a diode. The function relating the T_j to R_{on} can be extrapolated from the measurements of R_{on} and the acquired temperature at the same time instants. Such relation is used, in the next step, to evaluate the T_j and consequently the R_{thja}. The R_{on} characterization phase is performed with only the transistor in the on state, and it is

not influenced by the rest of the circuit. Other heat sources that change the temperature of the transistor during the working of the circuit can be detected performing an R_{on} measurement.

B. Thermal Faults Detection

During a test, a wrong assembling of the heatsink can be detected following the steps listed below:

1) Knowing the rated dissipated power of the transistor (R_{thjs}) and its nominal R_{on} ($R_{on_{nom}}$), it is possible to calculate the voltage V_{test} to apply on transistor. The power considered with such calculation is less than half of the nominal one. This reduces the probability of damaging the device if heatsink is incorrectly mounted.

$$V_{test} = \sqrt{\left(P_{rat}/2\right)^2 R_{on_{nom}}} \quad (2)$$

The value of V_{test} does not affect the test, and it is chosen conservatively to avoid damaging the transistor.

2) The ATE forces the gate-source voltage (V_{gs}) to the nominal high value of the gate driver in order to turn-on the power transistor.
3) The voltage V_{test} is applied to the DUT. During the test, the V_{ds} voltage and the Id current are monitored by the ATE, as shown in Fig. 3.
4) When the ratio between the V_{ds} and I_d reaches the steady-state (thermal equilibrium), the value of R_{on} is derived from the last measure of Vds and of Id as $R_{on} = V_{ds}/I_d$. The resistance R_{on} is used to evaluate T_j by $R_{on}(T_j)$ characterization.
5) The eq. 1 is used the evaluate the R_{thja}.
6) Finally, if the obtained value is larger than the maximum declared, a thermal fault is detected.

Fig. 3 shows the circuit implemented by the ATE to perform the test.

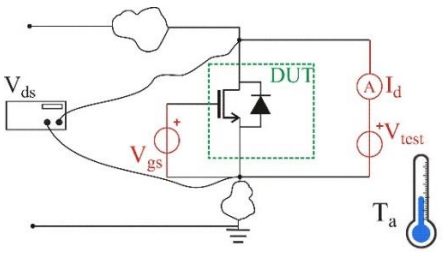

Fig. 3. ATE configuration for testing the heatsink mounting.

IV. Case Study

This section describes the circuit used to validate the introduced method. The circuit is an half bridge, i.e., it delivers an output voltage that is lower than the input one. The circuit is shown in Fig. 4.

The converter operates with an input voltage of 48 V and supplies a stable voltage of 12V. The maximum current that can be supplied by the converter is about 4 A. The power transistor considered is available in package TO-220. Its nominal R_{on} at 25 ℃ is 600 mΩ. The maximum junction temperature tolerable by the transistor is 150 ℃.

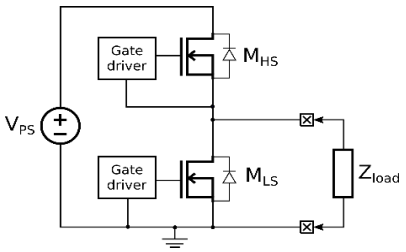

Fig. 4. Half bridge schematic.

V. Experimental Results

The proposed methodology has been experimented on one transistor of the case study shown in the previous section. Initially, as discussed in Section III, the power transistor is characterized in order to extract the relationship between the T_j and the R_{on}. For the sake of simplicity, since the tab of transistor is directly connected to the drain terminal, it is possible to approximate the junction temperature with the tab temperature during the cooling phase, as discussed in [24]. The Fig. 5 shows the T_j during the heating and cooling phases, while Fig. 6 shows the V_{ds} during the cooling phase. This characterization was performed for five different current levels, without and with heatsink. All the experiments highlight that the relationship is significantly not influenced by the power level and by the dissipating conditions, as shown in Fig. 7.

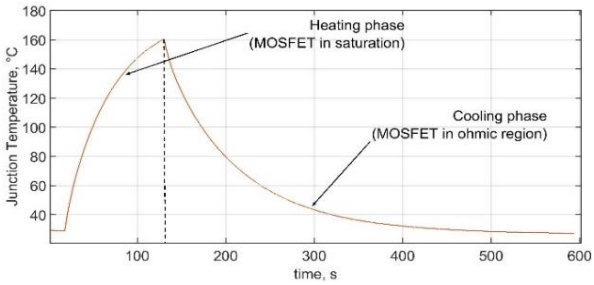

Fig. 5. Junction temperature in the heating and cooling phase during the calibration procedure

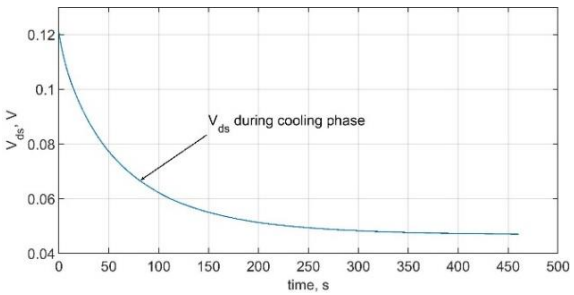

Fig. 6. V_{ds} in the cooling phase for calibration process.

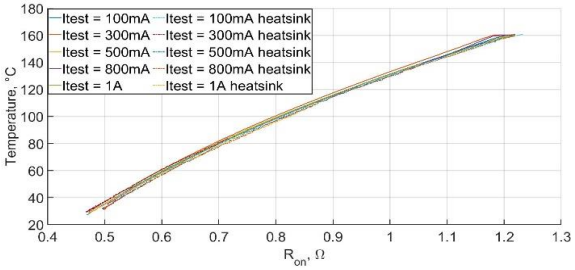

Fig. 7. Junction temperature as function of R_{on} with several current test and with and without heatsink

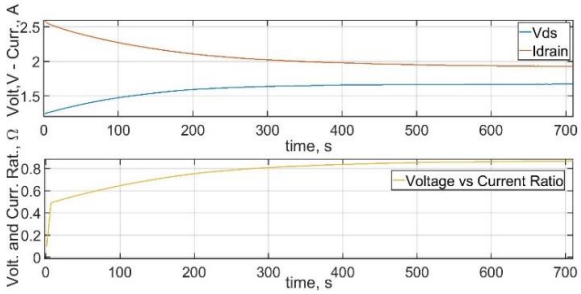

Fig. 8. Vds voltage and Idrain current during the test procedure.

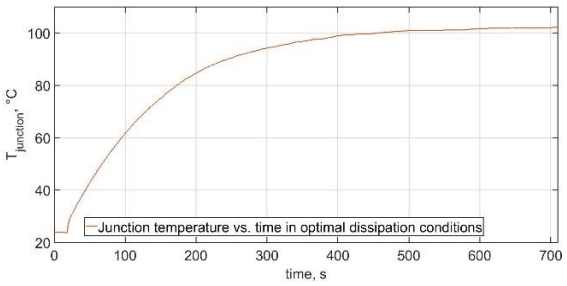

Fig. 9. Junction temperature during the test procedure.

In order to verify the effectiveness of the proposed approach, the DUT was configured for evaluating the thermal resistance in different dissipating conditions. In this analysis, the thermal resistance is evaluated with R_{on} measurements and with temperature evaluation, in order to compare the obtained results. Firstly, the transistor with an optimal mounting of the heatsink was characterized using four different power level. In such condition, the average value of R_{thja} measured using the temperature estimated with the thermocouple is 25.22 ℃/W (with a standard deviation of ±2 ℃/W), while the average value evaluated with the proposed approach is 26.17 ℃/W (with a standard deviation of ±1.44 ℃/W). The Fig. 8 shows the behavior of Vds, Idrain and of their ratio with the heatsink correctly assembled; in this chart, the transistor dissipating a power of 1.93W in steady-state. Instead, Fig. 9 shows the behavior of T_j during the test. It is possible to notice that the steady-state of the voltage and current ratio corresponds to the temperature steady-state, as expected.

Six different fault cases are experimentally considered. In each case a further heat obstacle between the heatsink and the tab of the MOSFET is voluntarily introduced. All the analyzed cases are reported in Table 1. In particular, the Case 1 refers to a metal washer placed between the tab and the heatsink to reduce the contact surface, while in the Case 2 the metal washer is replaced with a plastic one to reduce the thermal conductivity. In Case 3, the metal screw used to mount the heatsink until this point is replaced with a plastic one. In such case the plastic washer is still between the tab of the MOSFET and the heatsink. In Case 4 the heatsink is again mounted with metal screw but the couple between this one and the bolt is reduced. No obstacles are placed between the heatsink and the tab of the transistor. Finally, Case 5 and Case 6 consider a piece of paper between the heatsink and the tab of the transistor that covers half and all the contact surface respectively. As reported in Table I, all the fault cases show a good matching between R_{thja} evaluated using the measured temperature and the one estimated with R_{on}. With the proposed approach, all the considered fault cases are detected. In fact, all the estimated thermal resistances are out of the range of validity provided by the case of optimal mounting. The values reported in Table I were measured in the thermal regime; the system reaches the thermal regime in about 20 minutes.

VI. Conclusion

This paper introduces the concept of thermal fault in heat dissipation systems. An analysis of the thermal effects present on the transistor linked to a device overheating is provided. The overheating of a power device causes a rapid ageing and rapid damage of the transistor. For this reason, it is necessary to perform a test also for heatsinks; in particular, a test on the heatsink assembling is proposed in this paper. An in-circuit test methodology, using electrical measurements, is proposed in this paper. The proposed methodology can be implemented at the end of production by an ATE. The proposed methodology was evaluated on a power device performing accurate results and optimal capability of faults detection.

Conflict of Interest

The authors declare no conflict of interest.

Table I: Results Obtained from the Considered Cases

Case	V_{test} (V)	V_{ds} (V)	I_{ds} (A)	R_{on} (mΩ)	P_{diss} (W)	T_j (℃)	T_j (R_{on}) (℃)	T_a (℃)	R_{thja} (℃/W)	R_{thja} (R_{on}) (℃/W)
Optimal Dissipation	1.86	1.67	1.93	865	3.22	104.8	110.1	23.1	25.34	26.99
	1.09	0.94	1.52	623	1.44	62.9	63.2	23.2	27.55	27.75
	0.634	0.53	1.04	510	0.55	37.6	37.6	23.6	25.35	25.35
	2.59	2.38	2.10	1130	4.99	137.2	147	24.0	22.65	24.61
Case 1	1.16	1.01	1.51	675	1.52	73.8	74.2	23.9	32.69	32.95
	0.635	0.53	1.02	523	0.54	43.6	40.0	24.1	35.87	29.24
	1.81	1.63	1.76	926	2.86	112.2	119.2	24.2	30.75	33.19
	2.62	2.43	1.91	1270	4.64	155.2	160.0	24.3	28.20	29.24
Case 2	1.22	1.08	1.44	750	1.55	88.1	89.1	24.1	41.15	41.78
	1.82	1.66	1.62	1020	2.69	127.9	133.3	25.2	38.19	40.20
Case 3	1.33	1.18	1.46	808	1.72	96.4	99.5	25.3	41.27	43.06
	1.82	1.66	1.62	1020	2.69	127.9	133.3	25.2	38.19	40.20
Case 4	1.27	1.11	1.6	693	1.77	75.8	78.1	25.3	28.43	29.72
Case 5	1.28	1.12	1.62	694	1.82	76.1	79.0	25.0	28.03	29.62
Case 6	1.20	1.06	1.52	695	1.60	77.2	79.5	25.0	32.52	33.95

AUTHOR CONTRIBUTIONS

All the authors contribute equally to the implementation of such work, both for bibliographic research, the experimental sessions and for drafting of the paper. All authors had approved the final version.

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