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THERMAL ANALYSIS OF NEW SILICON-BASED SUBSTRATES

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Abstract: *New packaging concepts are required for power electronic modules allowing to dissipate high loss power density levels at low operation temperatures. Best heat removal from a substrate is obtained using liquid coolants. However, in this way the heat transfer coefficient is limited by the Leidenfrost phenomenon. A promising attempt to improve the thermal transfer significantly is the development of silicon substrates structured with microwhiskers perpendicular to the surface. However, an industrial application of this new technology for heatspreaders in power electronic modules makes necessary the specification of the substrate properties. In this work a new method for determination of thermal qualities based on laser heating of the heatspreader, surface temperature measurement by thermovision, and dynamic reverse modelling is described. Based on these results prospectively possible applications and limits of such heatspreaders for power electronics assemblies are derived.*
Keywords: Microwhiskers, thermal simulation, thermovision.

1 INTRODUCTION

General tendencies in the developments of power electronics are the continuing miniaturisation and enhancement of power densities. Frequently cited applications for new substrate technologies with enhanced thermal performance are e.g. power semiconductor lasers where optical characteristics are affected by temperature gradients inside of the component [1], and insulated-gate-bipolar transistors (IGBTs) for power control assemblies where loss power densities of more than 100 W/cm^2 have to be removed not exceeding a junction temperature frequently of less than 125°C. In either case the highest possible heat transfer coefficient between component and cooling agent is required. For this purpose packaging concepts based on a new substrate technology are needed. The highest heat transfer rates are obtained using liquid coolants. For best thermal performance even substrates with microchannels are used [2]. Drawbacks of such rather complex structures are costly manufacturing techniques and serious limitations of the flow rate, since the flow resistance rises dramatically with decreasing cross-section. However, the heat transfer rate is limited by the onset of boiling. A promising attempt to improve the thermal transfer coefficient significantly and thus, to allow to reduce the substrate-to-coolant heat transfer area is the development of silicon substrates structured with microwhiskers perpendicular to the surface. The whisker geometry can be varied widely by manufacturing parameters. In figure 1 a sample demonstrate such whiskers with about 40 µm spacing and a height of about 70 µm. The origin of silicon whisker growth goes back to the early sixties [3]. Recently, the application of whisker structured substrates as a heat sink assembly has been patented [4]. Some basic studies showing the thermal significance of the whisker structure have been carried out.

However, in order to open up this new substrate technology for industrial power electronics applications a method for sufficiently accurate specification of the thermal properties under defined boundary conditions must be available and relations between whisker geometry, flow rates of cooling agent, and heat transfer coefficient must be investigated to allow optimization of the microwhisker structure for the respective application.

According to these demands in this paper a new method for the determination of the heat transfer coefficient between substrate and cooling agent is presented which is based on heating the substrate with a Nd:YAG laser, temperature measurement using a thermovision system, and dynamic reverse thermal modeling.

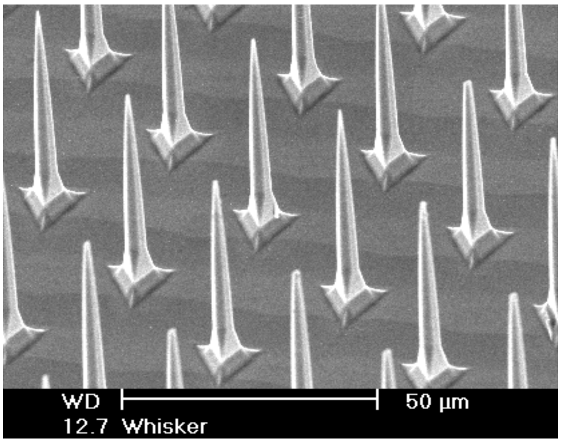

Figure 1. SEM view under 40° with respect to the perpendicular axis of a silicon heatspreader after whisker treatment. Height of whiskers: 70 µm, horizontal spacing: 40 µm, spacing of rows: 23 µm.

2 STATE-OF-THE-ART METHODS

In-situ methods for determination of thermal qualities like the Ångström method or the 3ù method are based on heating a specific test object with a modulated heat source and temperature measurement at a low number of distinct points [5]. In this way and under certain boundary conditions a simple analytic relation between the unknown characteristics and measured temperature-versus-time functions of the object are obtained. These methods are applicable only if the heat flow caused by the measured temperatures remains essentially inside of the tested object. However, this does not apply to substrates cooled by a liquid agent which also takes part at the lateral heat transport. Moreover, the mentioned methods do also not allow to consider non-uniform surface quality as it is the case if microwhiskers don't cover the whole surface but are grown according to a certain layout.

An extensive thermal characterization considering temperature dependencies of material properties, including the determination of heat transfer coefficients under the condition of a flowing cooling agent needs the measurement of the whole surface temperature distribution followed by comparison with results of thermal simulations. According to these demands we developed a new method for the determination of the heat transfer coefficient between substrate and coolant as presented in the following sections.

3 DETERMINATION OF THE HEAT TRANSFER COEFFICIENT

3.1 Experimental set-up

For our investigations we used an experimental set-up as shown in figure 2. The sample is mounted on a cooling duct. To obtain a well defined flow profile a special cooler has been fabricated by precisely crimping and flattening a tube with a diameter of 20 mm. In this part of the tube a window was milled such that the whisker structured substrate plane coincide with the inner surface of the cooler. In this part the cross section was 1 mm x 28 mm. A valve and a flow meter allowing to apply flow rates up to 450 liters per hour were used (not shown in the figure). The front side of the substrate was irradiated by the Nd:YAG laser. The transversal distribution in the spot was controlled by the laser power and a focusing lens. In order to allow contactless temperature measurement with a thermovision system the laser beam was deflected into the optical axis with a miniaturized mirror at a short distance above the substrate. In order to eliminate measuring uncertainties due to varying emissivity the substrates were coated with an absorptive high-temperature resistant varnish known from former experiments [6].

A measuring cycle is started by the control unit which opens the laser shutter and simultaneously remote controls recording with the thermovision system. In this way both, sequences of temperature values at arbitrary points as well as spatial temperature distributions can be obtained. Frequently the laser power is measured in the vicinity of the resonator. In our experiments we established the actual laser power close to the substrate surface with a flat calorimeter to avoid inaccuracies due to unknown losses at optical components between laser and target. To avoid measuring uncertainties experiments were carried out with a silicon substrate partially structured with whiskers, in the following termed "whisker structured substrate" (WS) and silicon substrates with one surface polished used as reference samples (RS). The substrates' dimensions were 25 mm x 25 mm x 400 µm. For test purposes, the cooled surface of the WS was divided into an area of about 50% structured with microwhiskers while the complement area remained untreated.

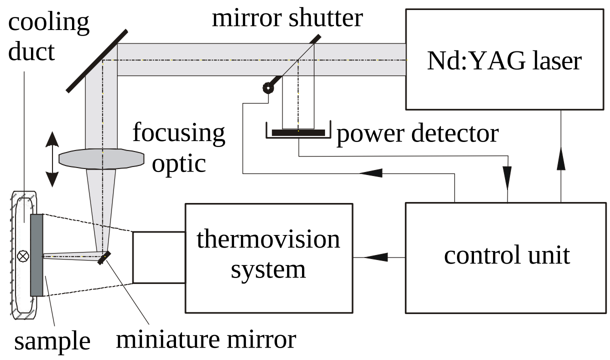

Figure 2. Experimental set-up.

3.2 Reverse thermal modeling

In order to establish the heat transfer coefficient *a* according equation 1 the temperature at the interface between silicon substrate must be known:

$$f = a \cdot (T_W - T_C) \tag{1}$$

Herein Ö is the heat flow density, T_W is the temperature of the whisker layer and T_C the coolant temperature. While T_C is constant and easy to determine, Ö and T_W are functions of space and time and can be determined only by reverse modeling using the measured surface temperature. As already mentioned the cooled surface of the WS consisted of whisker structured and unstructured parts. In order to describe the heat transfer, therefore, two different heat transfer coefficients had to be considered: $á_{ù}$ for the whisker structured part and $á_o$ for the remaining area. The layout of the whisker structure was considered accurately by the thermal model. In order to reduce the effort for model creation an easy discretization method has been used as developed in a previous work [7]. As a new approach in this work an alternating-direction implicit (ADI) algorithm was implemented which is capable of computing steady-state and transient heat transfer problems. The general idea of this numerical computation method is to attack the multi-dimensional problem in such a way that only one-dimensional computations are required [8]. This idea has led to the development of a great variety of ADI-methods. However, each of these methods show a different stability and convergence behavior and must be suited to the respective application. In our case a short and effective model-creation-modification cycle was essential resulting in a high node number. The developed algorithm allows to compute this high node numbers very efficiently.

4 DISCUSSION OF RESULTS

The two diagrams below (figure 3: reference substrate RS, figure 4: substrate with microwhisker structure WS) show the result of the reverse modeling procedure for a laser power level of 6 W at a laser spot diameter of 2.5 mm. The experiments were carried out at a water flow rate of 100 liters per hour. As depicted in the figures the temperature increase as a function of time was compared at two different points of the surface located at a distance of 3.8 mm (SP03) and 10.1 mm (SP01) to the laser beam axis. For temperature measurement a thermovision system (AGEMA 900) was used. As a result we obtained the heat transfer coefficients of $á_{ù}$ = 3800 W/m^{2}K for the whisker structured part and $á_o$ = 2700 W/m^{2}K at the polished surface.

The best agreement at a laser power level of 33 W for RS and 34 W for WS were obtained by setting $á_{ù}$ to 5700 W/m^{2}K. Figure 5 and 6 are demonstrating the calculated steady-state temperature distributions of the cooled interfaces in comparison. The parameters were set according to the respective experiments (carried out at a flow rate of 400 liters/hour).

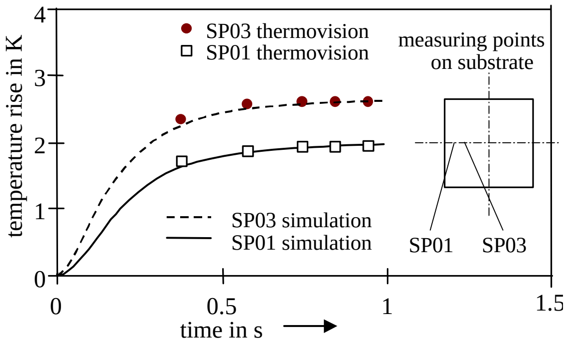

Figure 3. Comparison between thermovision measurement and simulated temperatures at RS, laser power: 6 W, cooling water temperature: 9°C, $á_o$ = 2700 W/m^{2}K.

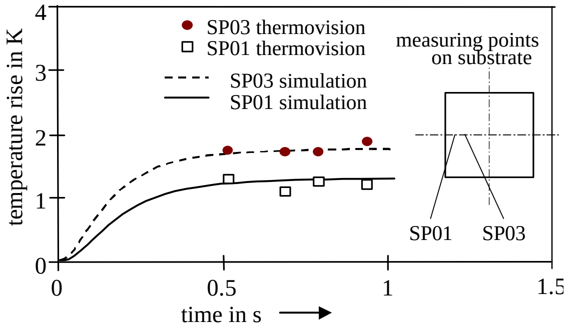

Figure 4. Comparison between thermovision measurement and simulated temperatures at WS, laser power: 6 W, cooling water temperature: 10°C, $á_ù$ = 3800 W/m^{2}K.

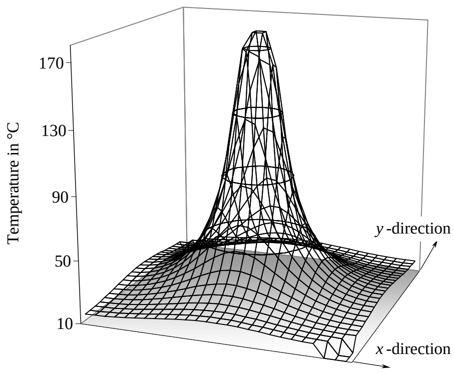

Figure 5. Calculated interface temperature at RS, laser power: 33 W, cooling water temperature: 9°C.

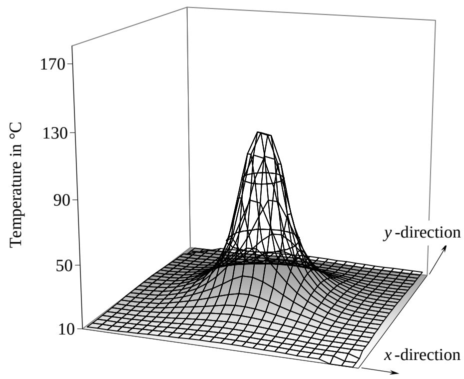

Figure 6. Calculated interface temperature at WS, laser power: 34 W, cooling water temperature: 10°C.

The influence of the flow rate of the cooling liquid on the heat transfer coefficient was also observed. According to the theory no influence should exist for laminar flow. By contrast, at the WS there was a significant increase of $á_ù$ with rising flow rate. We explained this by the high velocity of the flow at the whisker tips. From a theoretical investigation of the flow rate distribution in the vicinity of the whisker tips we derived a peak velocity of about 1.6 m/s at the tips which is assumed to cause turbulent flow. In this case the heat transfer coefficient increases with the flow rate.

5 VISION OF FUTURE APPLICATIONS

Low thermal resistances between source of loss power and ambient are increasingly important in many different applications. In the following some general aspects are discussed to highlight possibilities for future applications.

Until now, chips in power transistors commonly are attached on copper heatspreaders by soldering. Main advantage of this kind of mounting technique compared to adhesive bonding is a high thermal transfer coefficient between chip and heatspreader. However, an essential drawback is the large difference of thermal expansion coefficient between silicon and copper leading to a progressively diminishing thermal conductivity of the solder [9]. This could be avoided using silicon heatspreaders.

In an ingeniously constructed, liquid-nitrogen cooled multi-chip module the temperature increment at the hottest point is only 50 K caused by a loss power density of 24 W/cm^2 [10]. Herein, the loss power is conducted to the cooling agent across an insulating layer and the case lid. After proving the compatibility of the production steps for the whisker structure and the manufacturing techniques used for the electronic structure the WS could fulfil both functions in one substrate, the electronic and the thermal functions. In this way the thermal performance could even be surpassed: The increment of the junction temperature due to a loss power density of 100 W/cm^2 could be less than 1 K.

These examples demonstrate exemplarily the superiority of silicon heatspreaders with whisker structure in many areas of power electronics packaging from physical reasons. Thus, we believe in high chances of an economically interesting market for this new heatspreader technology.

CONCLUSION

General tendencies in the development of power electronics are outlined in the introduction. As a main problem, the combination of high density and low operation temperature was named. A new heatspreader technology based on silicon substrates structured with microwhiskers is suggested, however an industrial application presupposes thermal characterization of these substrates. Main goal of this work was to develop an adequate thermal analysis procedure based on laser heating of the substrates and establishing the respective thermal characteristics by reverse modeling. Particularly, the heat transfer coefficient between silicon substrate and liquid cooling agent is found to be increasable at least by a factor two. At power densities leading to interface temperatures closed to the boiling point of the cooling agent even higher factors can be achieved. Finally, chances for future industrial applications in power packaging are evaluated.

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