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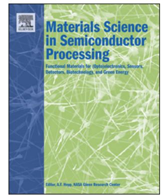

Review

# Thermal microscopy of electronic materials

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ABSTRACT

Due to an increasing level of device integration and progressive device miniaturization, the thermal management requires comprehensive microscopic investigations of thermal properties as heat dissipation on the micro- and nanoscale. Today heat management is one of the key limiting factors in a wide range of electronic applications, e.g. in automotive and electro-mobility. In this review, an overview on far-field and near-field thermal microscopy techniques using infrared thermography, laser beam techniques, and scanning probe microscopy is given. The common aim of all these approaches is to get access to temperature distributions, heat transport mechanisms, thermos-elastic quantities, as well as thermoelectric properties of electronic materials on microscopic levels. Examples for devices inspections, for integrated circuit analysis, and for thin film technology applications at micro and nanoscale are presented.

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## 1. Introduction

Today emerging technologies are required for thermal management of all kinds of electronic devices and circuits. Aside from challenges to develop new materials, innovative comprehensive

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failure and reliability investigations are mandatory to get access to the thermal properties of devices and systems as a whole. This is particularly obvious in the case of increasing device integration and progressive miniaturization. In this regard, the rise of portable devices has driven new research and development efforts into devices and materials, because there is an industry trend to add more functionality into the smart-phones, while constantly reducing their size and weight. In addition, thermal management becomes more and more important in automotive and electro-mobility applications. Heat dissipation is at this time the key limiting factor for power electronics, including high-power RF devices as well as in high-power laser diodes and high-brightness light-emitting diodes (LEDs).

There are a lot of efforts in active cooling systems as well as in using materials with high thermal conductivities such as diamond or graphene for heat spreading. Furtheremore, the class of electronic materials includes electrical insulators, semiconductors, as well as conductors. They can be crystalline solids, amorphous materials, organic materials, as well as combinations of these. A general challenge is related to thermal stresses in electronic components and films which arise primarily from different coefficients of thermal expansion [1]. For insulators and semiconductors, heat is typically transported by atomic lattice vibrations, the energy quantum of which is known as a phonon, while in conductors heat is conveyed by charge carriers such as electrons and holes. The thermal conductivity of the materials ranges from $0.1\,\frac{\mathrm{W}}{\mathrm{mK}}$ such as in epoxy, over $400\,\frac{\mathrm{W}}{\mathrm{mK}}$ for copper to more than $2000\,\frac{\mathrm{W}}{\mathrm{mK}}$ in the case of diamond (the word wide largest thermophysical property data are provided by DETHERM [2]). A discussion focused on the thermal conductivity of 3D cubic crystals, 2D layered materials, nanostructure networks and composites, aligned polymer fibers, and molecular layers as well as the property dependence on structure, size scaling, physical state, or environment has been given in a recent article [3].

Although the effectiveness of a heat spreading is often directly related to the thermal conductivity of the used materials, alternative passive means of cooling were sought [4]. One is to use materials with an elevated specific heat. A different procedure is to use solid–liquid organic phase change materials. It is suggested with regards to the thermal management of mobile phone, that dissipating heat from the electronic components, which is of a periodic nature or a sudden transient, can be effectively stored by this high latent heat of melting [5]. The practical applications of liquid-phase-exfoliated graphene as filler material in phase change materials have been recently outlined [6]. A review of the thermal properties of graphene, few-layer graphene and graphene nanoribbons, and discussion of practical applications of graphene in thermal management and energy storage is also given within this paper.

Today, there is still a continuing procedure of developing new materials with certain thermal characteristics which have to be inspected by means of sophisticated thermal characterization techniques. The common theoretical framework is based on the work of Fourier [7]. All techniques provide a heat source at the surface or within the volume of an electronic material. Hence, for a given temperature distribution $T(\vec{r})$, the heat flux $\vec{q}$ is classically described as normal diffusive transport for bulk materials by the Fourier law [8]:

$$\vec{q}=-\vec{\lambda}\bullet gradT(\vec{r}) \tag{1}$$

here, $\vec{\lambda}$ is the tensor of thermal conductivity. Furthermore, techniques to measure thermal properties can be divided into two main categories: steady-state techniques and transient techniques. For the former, the thermal conductivity can be directly determined, if the absorbed power in the sample is known. For the latter, the specific density $\rho$ as well as the specific heat $c$ of the material must be considered and the heat flow is described by the general equation of heat conduction:

$$\rho c\frac{\partial T(\vec{r})}{\partial t} = \frac{\partial}{\partial x}(\lambda_x\frac{\partial T(\vec{r})}{\partial x}) + \frac{\partial}{\partial y}(\lambda_y\frac{\partial T(\vec{r})}{\partial y}) + \frac{\partial}{\partial z}(\lambda_z\frac{\partial T(\vec{r})}{\partial z}) + \dot{q}_E \tag{2}$$

where $\dot{q}_E$ indicates the amount of heat generated per unit time and unit volume. Since only the derivative of $T(\vec{r})$ appears in this equation, the knowledge of the absolute temperature and the absorbed power is not required. It must also be noted, Eq. (2) can only be simplified to

$$\frac{\partial T(\vec{r})}{\partial t} = a\bullet\Delta T(\vec{r}) + \frac{\dot{q}_E}{\rho c} \tag{3}$$

is in the case of assuming homogeneous and isotropic materials, whereby $a=\frac{\lambda}{\rho c}$ denotes the thermal diffusivity of the material, the ability of a material to conduct thermal energy relative to its ability to store thermal energy which is usually proportional to a characteristic decay time of the thermal system.

The heat flux strongly depends on the dimensionality of the electronic materials and is of growing interest with shrinking devices and in thin film technology. Some contradicting descriptions of this matter exist in literature. While a decrease of the thermal conductivity has been reported for dielectrics and semiconductors with decreasing structure sizes of less than 2 μm [9,10], it was stated on the contrary that the thermal conductivity of metal and organic films are independent of the film thickness down to 20 nm [11]. For nanoscale structures with sizes below the mean-free path of the phonons $l_{phonon}$, also referred to as Casimir limit [12], the above mentioned diffusive heat transport description has been predicted to fail and some ambiguities exist in the theoretical explanations. An overview of fundamentals and engineering applications of microscale and nanoscale heat transfer is summarized by Sobhan and Peterson [13]. A review on the applied physics of thermal transport at the nanoscale which emphasized developments in experiment, theory, and computation is given by Cahill et al. [14].

It is well known that ballistic phonon transport becomes important in structures within these small feature sizes. In this regime, it is concluded that heat conduction by lattice vibrations or phonons behaves like radiative transfer [15]. Hence the heat flux is described separately by the Stefan–Boltzmann Law [16]:

$$q = \sigma T^4 \tag{4}$$

where $\sigma$ is the Stefan–Boltzmann constant for phonons, which was calculated by Swartz and Pohl [17] in studies of thermal boundary resistances. At low temperatures and in isotropic condensed matter $\sigma$ is given by

$$\sigma = \frac{\pi^2 k_B^4}{120\hbar^3}\sum_i \frac{1}{c_i^2} \tag{5}$$

here $k_B$ is Boltzmann's constant, $\hbar$ is Planck's constant divided by $2\pi$ and $c_i$ is the respective speed of sound, in longitudinal and transverse direction.

In summary, it can be emphasized, that the Fourier law is only valid for steady-state heat conduction in the acoustically thick limit and the macroscale regime, where the film thickness is much larger than the phonon mean free path in a bulk material. If the probability of phonon scattering is very low, the law of blackbody radiation must be applied. Since no combined accurate theoretical approach is available for all length and timescales, it is still a great challenge to describe heat transport from the ballistic regime to diffusive heat transport [18].

Moreover, inevitably far-field and near-field thermal

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