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Pulse transient hot strip technique adapted for slab sample geometry to study anisotropic thermal transport properties of \(\mu\)m-thin crystalline films

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A new method based on the adaptation of the Pulse Transient Hot Strip technique to slab sample geometry has been developed for studying thermal conductivity and thermal diffusivity of anisotropic thin film materials (<50 \(\mu\)m) with thermal conductivity in the 0.01–100 W/mK range, deposited on thin substrates (i.e., wafers). Strength of this technique is that it provides a well-controlled thermal probing depth, making it possible to probe a predetermined depth of the sample layer and thereby avoiding the influence from material(s) deeper down in the sample. To verify the technique a series of measurements were conducted on a y-cut single crystal quartz wafer. A Hot Strip sensor (32-\(\mu\)m wide, 3.2-mm long) was deposited along two orthogonal crystallographic (x- and z-) directions and two independent pulse transients were recorded. Thereafter, the data was fitted to our theoretical model, and the anisotropic thermal transport properties were determined. Using a thermal probing depth of only 30 \(\mu\)m, we obtained a thermal conductivity along the perpendicular (parallel) direction to the z-, i.e., optic axis of 6.48 (11.4) W/mK, and a thermal diffusivity of 3.62 (6.52) mm²/s. This yields a volumetric specific heat of 1.79 MJ/mK. These values agree well with tabulated data on bulk crystalline quartz supporting the accuracy of the technique, and the obtained standard deviation of less than 2.7% demonstrates the precision of this new measurement technique.

I. INTRODUCTION

For studying bulk thermal transport properties of solids, transient methods have become increasingly popular and useful since they can handle limited sample sizes (typically 1–10 mm thick), and are insensitive to the thermal contact resistance between the heating/sensing element(s) and the sample surface. The rather simple sample preparation and heat/sensor element fixation to the sample has led to many commercially available instruments based on transient methods.1–4

To study samples that are thinner, i.e., thickness < 100 \(\mu\)m, and which have relative high thermal conductivity, i.e., \(\lambda > 1 \text{W/mK}\), a number of transient methods have been developed or specially adapted, including the Pulse Transient Hot Strip (PTHS) method,5–7 Three-Omega method,8 and the Thermo-Reflectance method.9 However, among these only the PTHS method can be used to deduce anisotropic thermal transport properties, from a single transient recording.10

While for Transient Line Source techniques, like the Three-Omega method, or Transient Point Source techniques, like the Thermo-reflectance method, only one thermal transport property is retrieved. Moreover, Transient Plane Source methods have the advantage of a clearly defined thermal probing depth (as described in Sec. II), making it possible to certify that the measurement results are not influenced by the thermal properties of the material(s)/substrate below the thin layer under investigation.

In the PTHS method a thin micrometer-wide metal strip, a so-called Hot Strip sensor, is deposited on the surface of the sample layer, acting both as the heating and sensing element. While an electrical current, consisting of series of square pulse trains of low duty cycle, passes through the sensor, the average temperature increase in the sensor is monitored via its increased electrical resistance. The recorded average temperature rise as a function of pulse length is thereafter fitted to a theoretical model, wherefrom both the thermal conductivity and thermal diffusivity of the sample layer can be extracted.11

In this work we have extended the theory behind the PTHS method so that it does not assume that the thin sample layer is placed on an “infinitely” thick substrate, but instead handles the case where the layer is placed on a thin substrate attached to a heat sink. This technique is referred to as Slab PTHS method and it opens up the possibility to study a wide range of anisotropic material (e.g., crystalline) structures grown on thin wafers (typically 200–600 \(\mu\)m thick). This is of interest, for example, to the semiconductor industry in their continuous efforts to develop/optimize complex layered structures for electronic and photonic devices.

To demonstrate the Slab PTHS technique, the paper is organized as follows: Sec. II contains a discussion on the thermal probing depth; Sec. III outlines the theory; Sec. IV...
achieved. Further, the heating current through the sensor thermal conductivity from the single transient recording is the highest accuracy of the retrieved thermal diffusivity and closely approximates the desired probing depth, because then the highest accuracy of the retrieved thermal diffusivity and thermal conductivity from the single transient recording is achieved. Further, the heating current through the sensor must consist of close-to-ideal square pulse(s) to make sure that the thermal probing depth matches the strip width (disc radius).

A relevant question is then how deep into the sample the thermal properties are recorded when performing the transient recording. Carslaw and Jaeger discussed the “mean square distribution of heat” while the more useful concept of “probing depth” has recently been introduced and is defined as

\[ \Delta p = k \cdot (\kappa \cdot t)^{1/2}, \]  
(1)

where \( k \) is a constant dependent on the experimental method and the sensitivity by which the temperature increase in the heating/sensing element is recorded, \( \kappa \) is the thermal diffusivity, and \( t \) is the length of the square pulse used in the experiment. For Transient Plane Source techniques the constant \( k \) is regularly fixed to the value of 2. From this expression it follows that for a given material with a certain thermal diffusivity, the thermal depth of probing into a sample is determined by the current pulse length applied to the heating/sensing element.

From Eq. (1) it is also clear that if the aim is to reduce the probing depth from 10 mm down to 10 \( \mu \)m, i.e., three orders of magnitude, for the same sample material, it is necessary to reduce the current pulse length from the typical range of seconds down to microseconds. A convenient way of working with such short pulses was demonstrated by Gustafsson et al., who used an AC coupled network originally devised by Rosenthal and also used by researchers at Bell Laboratories. This PTHS method has proven successful in handling the electrical aspects of the use of micrometer-wide Hot Strip sensors exposed to trains of microsecond square-shaped current pulses of duty cycle around 5%, and is the basis of this work.

II. THERMAL PROBING DEPTH

There are specific requirements on performing thermal transport property measurements using Transient Plane Source techniques, like the Transient Hot Strip and Hot Disc techniques. In particular, it is necessary to use a thin Hot Strip (Hot Disc) sensor, which acts both as heating and sensing element, of a width (disc radius) which closely approximates the desired probing depth, because then the highest accuracy of the retrieved thermal diffusivity and thermal conductivity from the single transient recording is achieved. Further, the heating current through the sensor must consist of close-to-ideal square pulse(s) to make sure that the thermal probing depth matches the strip width (disc radius).

Here, \( t \) is the time measured from the beginning of the square current or power pulse, which is heating the strip. Parameter \( \lambda_1 \) denotes the thermal conductivity and \( \kappa_1 \) denotes the thermal diffusivity (utilized later in Eq. (11)), both perpendicular to the plane on top of which the strip has been deposited (often referred to as the through-plane direction). Parameters \( \lambda_2 \) and \( \kappa_2 \) are the thermal conductivity and thermal diffusivity, respectively, parallel to the plane on top of which the strip has been deposited (often referred to as the in-plane), but perpendicular to the length of the extended strip.

It is here assumed that the strip is heated by a train of ideal square pulses of low duty cycle (typically 5%) produced by a pulse generator. The electrical circuit used in this AC-coupled network is depicted in Fig. 1, where the AC-coupling is achieved by using a DC block.

The pulse generator, which is assumed to produce time limited ideal square pulses of constant voltage \( V \) while having a constant internal resistance \( R_S \), is represented by \( V \) and \( R_S \) in Fig. 1. The resistance of the Hot Strip sensor can be described by \( R(t) = R_0 + \Delta R \), where \( \Delta R \) is the resistance increase caused by the temperature increase resulting from the direct Joule heating. The resistance, \( R \), of the Hot Strip sensor exposed to a small temperature increase, \( \Delta T \), can also be expressed as

\[ R = R_0 \cdot [1 + \alpha \cdot \Delta T], \]
(4)

where \( \alpha \) is the TCR (Temperature Coefficient of the Resistivity), and thus

\[ \Delta R = \alpha \cdot R_0 \cdot \Delta T. \]
(5)

III. SLAB PTHS THEORY

The heating/sensing element is assumed to be a thin rectangular-shaped metal strip deposited on the top surface of a slab-shaped sample, and where the bottom surface of the slab sample is attached to a heat sink, i.e., the sample is placed on a platform that is kept at a constant temperature throughout the transient recording. The thickness of the sample is considered to range from several millimetres down to a fraction of a millimetre.

If the sample is anisotropic and homogeneous, and if the length \( (2h) \) of the strip is much larger, at least 20 times larger, than the width \( (2d) \) of the strip, the temperature increase of this element can be expressed as

\[ \Delta T(t) = \frac{Q}{2\sqrt{\pi \cdot h \cdot (\lambda_1 \cdot \lambda_2)^{1/2}}} \cdot f(t), \]
(2)

where \( Q \) is the total output of power in the strip and \( f(t) \) is an analytical function with

\[ \tau = (t/\theta_2)^{1/2} \text{ and } \theta_2 = d^2/\kappa_2. \]
(3)
With the notations given in Fig. 1 and the assumption that the pulse voltage $V$ is constant throughout a transient recording, the corresponding voltage over the Hot Strip sensor is $U(t) = U_0 + \Delta U$, where

$$\Delta U = \Delta R \cdot I_0 \cdot \left[ \frac{R_S}{R_S + R_0} \right],$$

provided $\Delta R$ is small compared with $R_S + R_0$.

The AC-coupled network ideally results in a square-shaped current pulse train passing through the Hot Strip sensor that is defined by the pulse period $P$, duty cycle $F$, and the pulse height, as shown in Fig. 2.

Because of the AC-coupling, the strip is exposed to a series of positive and negative current pulses, of which relative amplitudes are determined by the duty cycle. Let $I_+$ and $I_-$ be the positive and negative current excursions through the Hot Strip sensor for a fixed duty cycle $F$. With the driving voltage $V$ and the internal resistance of the pulse generator ($R_S$), we have

$$V = (R_0 + R_S) \cdot (I_+ - I_-)$$

and

$$I_+ \cdot F = -I_- \cdot (1 - F) \text{ (i.e. zero net charge condition).}$$

The negative or “reverse” current – together with an equivalent part of the current during the positive pulse excursions – create a constant output of power $R_0 \cdot (I_-)^2$, which after a large number of pulses will result in a constant “background” temperature difference ($\Delta T_b$) between the Hot Strip sensor and the temperature controlled platform, on top of which the slab sample has been placed. The thickness of the sample is assumed to be much larger than the thermal probing depth as calculated from the longest pulse length used in the transient recordings. The “background” temperature increase can be expressed as

$$\Delta T_b(t) = \frac{P_0 \cdot F}{2 \sqrt{\pi} \cdot h \cdot \left( \lambda_1 \cdot \lambda_2 \right)^{1/2}} \cdot f_S(t \tau_2 b),$$

where $P_0$ is the total output of power in the strip, and is related to the driving voltage $V$ via

$$P_0 = \frac{V^2 \cdot R_0}{(R_0 + R_S)^3}.$$
reached at the end of a pulse “on-state” will have time to relax back to the background temperature, \( \Delta T_b \), before the start of the next pulse “on-state.”. The time-dependent part of the temperature increase in the Hot Strip sensor during a pulse \( \Delta T(t) \) can then be described as

\[
\Delta T(t) = \Delta T_{tot}(t) - \Delta T_b = \frac{P_0}{2\sqrt{\pi} \cdot h \cdot (\lambda_1 \cdot \lambda_2)^{1/2}} \cdot \left[ f(\tau) - F^2 \cdot \beta \right]. \tag{15}
\]

Using Eqs. (5) and (6), the temperature increase \( \Delta T(t) \) can be obtained from the voltage increase over the Hot Strip sensor as

\[
\Delta T(t) = \Delta U(t) \cdot \frac{(R_0 + R_3)^2}{\alpha \cdot \nu \cdot R_0 \cdot R_S}, \tag{16}
\]

where the relationship \( I_0 = V/(R_0 + R_S) \) has been used.

By measuring the average voltage over a large number of periods, it is possible to get the average temperature increase over a full pulse period or over a pulse “on-state”. In the AC network, this is done with the nano-voltmeter with assistance of the low-pass filter. The average temperature increase in the Hot Strip sensor, \( \Delta T_{MV} \), over a full pulse period is

\[
\Delta T_{MV}(P) = \frac{P_0}{2\sqrt{\pi} \cdot h \cdot (\lambda_1 \cdot \lambda_2)^{1/2}} \cdot \frac{1}{P} \int_0^{FP} dt \cdot [f(\tau) - F^2 \cdot \beta]. \tag{18}
\]

It is here assumed that the temperature variation, above the “background” temperature during the part of the period when the pulse generator is idle, is obscured by the fact that the total “reverse” current is used to maintain the “background” temperature. The corresponding average temperature increase over a pulse “on-state” can then be expressed as

\[
\Delta T_{MV}(FP) = T_+ \cdot \frac{1}{FP} \int_0^{FP} dt \cdot [f(\tau) - F^2 \cdot \beta], \tag{19}
\]

where

\[
T_+ = \frac{P_0}{2\sqrt{\pi} \cdot h \cdot (\lambda_1 \cdot \lambda_2)^{1/2}}. \tag{20}
\]

Equation (19) can be expressed as

\[
\Delta T_{MV}(\tau_2) = T_+ \cdot \left( \frac{2}{\tau_2^2} \int_0^{\tau_2} dx \cdot x \cdot f(x) - \beta \cdot F^2 \right), \tag{21}
\]

using the transformation

\[
\tau_2 = \left( \frac{FP}{\theta_2} \right)^{1/2}, \text{ where } \theta_2 = \frac{d^2}{\kappa_2}. \tag{22}
\]

Equation (21) can be transformed to

\[
\Delta T_{MV}(\tau_2) = T_+ \cdot H(\tau_2) - \beta \cdot T_+ \cdot F^2 \tag{23}
\]

with

\[
H(\tau_2) = \frac{2}{\tau_2^2} \int_0^{\tau_2} dx \cdot x \cdot f(x). \tag{24}
\]

FIG. 4. Schematic top (above) and side (bottom) view of the heat sink platform with the quartz wafer placed on top, also illustrating the Hot Strip sensor layout and orientation with respect to the crystallographic axes of the wafer.

From Eq. (23) it can be seen that a plot of measured \( \Delta T_{MV}(\tau_2) \) (the mean value of the temperature increase in the Hot Strip sensor over a pulse “on-state”) versus calculated \( H(\tau_2) \) would give a straight line fit with slope \( T_+ \). Since the thermal diffusivity \( \kappa_2 \) is not known, an iteration process is initiated to find the \( \theta_2 \)-value, which gives the best straight line fit between measured \( \Delta T_{MV}(\tau_2) \) and calculated \( H(\tau_2) \), using the least square method. From the \( \theta_2 \)-value, which gives the best straight line fit, the “in plane” thermal diffusivity can be calculated from

\[
\kappa_2 = \frac{d^2}{\theta_2}. \tag{25}
\]

From the slope of the straight line, \( T_+ \), the product of the two thermal conductivities can be calculated:

\[
(\lambda_1 \cdot \lambda_2)^{1/2} = \frac{P_0}{2\sqrt{\pi} \cdot h \cdot T_+}. \tag{26}
\]

If the specific heat per unit volume, \( \rho C_p \), is measured in a separate experiment, it is possible to calculate the two conductivities and the two diffusivities in the principal directions. These directions should correspond to the orientations of the Hot Strip sensor, see Fig. 4. However, if the anisotropic sample is a uniaxial crystal – like single crystal quartz – and the Hot Strip sensor is oriented along the optic- (z-) axis, the measurement yields the thermal conductivity and the thermal diffusivity in the plane perpendicular to the optic-axis, and from their ratio the volumetric specific heat for the sample can be obtained, which is demonstrated below.

IV. MEASUREMENT SETUP AND PROCEDURE

A y-cut surface-polished single crystal quartz wafer (z-cut flat) from MTI Corporation, with diameter 2 in. and thickness 500 \( \mu \)m, was measured to verify the Slab PTHS method. The aim is to demonstrate the unique ability of the method to determine the anisotropic thermal conductivity and thermal diffusivity of a crystalline sample, only requiring a thermal
probing depth of less than 50 μm, which expands the capability to study μm-thin crystalline films.

Figure 4 shows a schematic of the Hot Strip sensor layout on the single crystal quartz wafer. A matrix of a double Hot Strip sensor pattern was distributed evenly on the surface of the y-cut quartz wafer. The double strip pattern was arranged such that one strip was oriented along the optic- (z-) axis (referred to as horizontal strip), and the other strip was oriented along the x-axis (referred to as vertical strip), of the crystal. A thermal probing depth of about 30 μm was the target. Therefore the strips were 32-μm wide (in order to maximize the sensitivity in the dual determination of the thermal conductivity and diffusivity from a single pulse transient recording, as discussed in Sec. II). To further ensure that systematic errors in the measured thermal transport properties are less than 1%, the strip length was 100 times longer than the strip width, i.e., 3.2 mm. The strips were fabricated by electron beam evaporation of 10 nm Ti (“adhesive” layer) and 97 nm Au, followed by a subsequent lift-off step. This yielded a strip resistance (R0) of ~32 Ω (which is not too far from a desired 50 Ω for impedance matching to the internal resistance of the pulse generator, Rs = 50 Ω). The quartz wafer was placed on an aluminium heat sink platform with precise temperature control by a Peltier element and a TEC controller. For ensuring good thermal contact between the wafer and the platform, a thin layer of thermal paste was used.

Electrical connections to the Hot Strip sensors were arranged with contact pads at the ends of the strips that were probed using micro-manipulated probe positioners (having a ball tip needle that can handle high DC currents) with the aid of a microscope. In the applied electrical circuit (Fig. 1) the DC block is designed such that AC-coupling is achieved, but without deforming the square-shaped pulses reaching the Hot Strip sensor, which requires a relative large capacitance. During the pulse transient recording, the voltage over the Hot Strip sensor varies quite substantially, especially as the applied pulse voltage is in the range 1–10 V. For this reason it was necessary to use a specially designed low-pass filter to comply with the performance of the nano-voltmeter, when recording the average voltage increase of the Hot Strip sensor. The particular instrumentation used for these measurements, as well as software for controlling the experiment and analysing the recorded data, was developed by Hot Disk AB.17

The measurements were conducted by first measuring the TCR value of the Hot Strip sensor, by scanning the heat sink platform temperature over a range of 20 °C around room temperature (22 °C) and simultaneously recording the change in sensor resistance. The TCR was ~0.0032 Ω/K, and also constant after exposing the Hot Strip sensors to a series of pulse transient recordings. Next, the heat sink platform temperature was stabilized at 22 °C, and a series of pulse trains of fixed voltage and duty cycle (5%), but of different pulse lengths, were applied to the Hot Strip sensor. The average voltage increase of the sensor for each pulse length was recorded by the nano-voltmeter. The average voltage increase is proportional to the average temperature increase of the Hot Strip sensor (ΔTMV), which is plotted in Fig. 5 versus pulse length (F · P). The pulse length was varied between 4 and 70 μs, where the longest pulse length yields a maximum temperature increase of ~1 K.

It should be noted that when recording the average voltage increase in the Hot Strip sensor for a particular pulse length, a certain number of “prior” pulse periods are required in the pulse train to ensure that the condition of having a constant “background” temperature, ΔTb, as expressed by Eqs. (9) and (12), is fulfilled, see also Fig. 3. Therefore, for the case in Fig. 5, with a 500-μm-thick single crystal quartz wafer, the number of “prior” pulse periods in a pulse train had to be around 100-200 periods, or more.

From the recorded average temperature increase of the Hot Strip sensor (ΔTMV) versus pulse length, the thermal transport properties are calculated via an iteration procedure as described in Sec. III, seeking the best straight line fit of a
TABLE I. Measured thermal conductivity and thermal diffusivity in direction perpendicular to the optic-axis of y-cut single crystal quartz wafer, using the Slab PTHS method with a thermal probing depth of 30 μm.

<table>
<thead>
<tr>
<th>Horizontal Strip No.</th>
<th>TCR (ΩK⁻¹)</th>
<th>Set pulse voltage (V/2) (V)</th>
<th>Output of Power (P₀) (mW)</th>
<th>ΔT (K)</th>
<th>λ⊥ (Wm⁻¹K⁻¹)</th>
<th>κ⊥ (mm²s⁻¹)</th>
<th>ρCp (MJm⁻³K⁻¹)</th>
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</thead>
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<tr>
<td>1</td>
<td>0.00320</td>
<td>1.7</td>
<td>55.1</td>
<td>0.750</td>
<td>6.512</td>
<td>3.616</td>
<td>1.801</td>
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<td>2</td>
<td>76.2</td>
<td>1.046</td>
<td>6.438</td>
<td>3.482</td>
<td>1.849</td>
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<td>101.0</td>
<td>1.397</td>
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<td>76.6</td>
<td>1.063</td>
<td>6.383</td>
<td>3.638</td>
<td>1.755</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.3</td>
<td>101.3</td>
<td>1.405</td>
<td>6.379</td>
<td>3.579</td>
<td>1.782</td>
<td></td>
</tr>
</tbody>
</table>

Mean Value 6.483 3.620 1.792
Std Dev% 1.56% 2.45% 2.24%

calculated dimensionless “time” function $H(\tau_2)$ to measured $\Delta T_{MV}$ for different pulse lengths. For the particular measurement data presented in Fig. 5, the obtained best straight line fit is shown in Fig. 6, where the standard deviation of the measurement data to the straight line is only 1.3 mK.

V. EXPERIMENTAL RESULTS

A series of pulse transient recordings at different pulse voltages were conducted on three different horizontal, and three different vertical, Hot Strip sensors. The measurement conditions and results when using the horizontal strips are summarized in Table I. For each pulse voltage, two individual recordings were made and the average values from these two recordings are tabulated. Since the horizontal strip is oriented along the optic- (z-) axis, the extracted thermal diffusivity is for x-direction (see Fig. 4, and Eq. (25)) and the extracted thermal conductivity product (see Eq.(26)) is for x-y-direction. But because of single crystal quartz being a uniaxial crystal, the material properties along the principal x- and y-axis are identical, and therefore the results directly yield the thermal conductivity ($\lambda_\perp$) and thermal diffusivity ($\kappa_\perp$) perpendicular to the optic-axis. In addition, from their ratio we can determine the volumetric specific heat of the single crystal quartz, which would not be possible if the sample was a biaxial crystal. To limit the thermal probing depth to $\sim 30 \mu m$ (i.e., close to the width of the strip) a maximum pulse length of 70 μs was used, and to achieve a temperature increases of $\sim 1 K$ over this pulse length, an instrument set pulse voltage ($V/2$ referring to Fig. 1) around 2 V was needed. A temperature increase of 1-2 K is typically required when working with TPS techniques to avoid impairments from Johnson noise. Moreover, as can be observed in Table I, no deterministic change of the extracted thermal transport properties was found when varying the instrument set pulse voltage around 2 V, which supports the theory behind the method.

Table II summarizes the corresponding measurement conditions and results when using the vertical strips. In this case the strip is oriented along the x-axis, wherefore the extracted thermal diffusivity is for z-direction and the extracted thermal conductivity product is for z-y-direction. This means that we obtain the thermal diffusivity parallel to the optic-axis ($\kappa_\parallel$), and the geometric mean value of the thermal conductivity parallel and perpendicular to the optic axis ($\sqrt{\lambda_\perp \lambda_\parallel}$). Because of the higher thermal diffusivity and thermal conductivity in these directions, a shorter maximum pulse length

TABLE II. Measured thermal conductivity and thermal diffusivity in direction parallel to the optic-axis of y-cut single crystal quartz wafer, using the Slab PTHS method with a thermal probing depth of 34 μm.

<table>
<thead>
<tr>
<th>Vertical Strip No.</th>
<th>TCR (ΩK⁻¹)</th>
<th>Set pulse voltage (V/2) (V)</th>
<th>Output of Power (P₀) (mW)</th>
<th>ΔT (K)</th>
<th>$\sqrt{\lambda_\perp \lambda_\parallel}$ (Wm⁻¹K⁻¹)</th>
<th>$\kappa_\parallel$ (mm²s⁻¹)</th>
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<td></td>
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<td>2.5</td>
<td>119.3</td>
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<tr>
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<td>0.00322</td>
<td>2</td>
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<td>119.0</td>
<td>1.375</td>
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</tbody>
</table>

Mean Value 8.612 6.524
Std Dev% 1.05% 2.63%
of 50 μs and a somewhat higher pulse voltage was used to
reach a ~30 μm thermal probing depth and to achieve ~1 K
temperature increase.

Table III summarizes the measured anisotropic thermal
transport properties of the y-cut single crystal quartz wafer,
using a thermal probing depth of only ~30 μm. The results
are taken as the mean values from all data presented in Ta-
bles I and II. In order to obtain the thermal conductivity in
the direction parallel to the optic axis (λ∥), the values of the
thermal conductivity from both Tables I and II were used.
The obtained experimental data with the Slab PTHS method
are quite close to earlier published data on anisotropic ther-
mal transport properties of bulk single crystal quartz, see,
e.g., Refs.11, 18, and 19. The results also imply that the y-
cut wafer under test does not display any structural defects
within the investigated probing depth (~30 μm), since ther-
mal transport properties are sensitive to even slight deviations
from an ideal crystalline structure. Further, the low standard
deviation in the obtained thermal transport properties, <2.7%
for all properties, demonstrates the high precision of the Slab
PTHS technique.

VI. CONCLUSIONS

In this paper, we have presented a new measurement
 technique, referred to as Slab PTHS method, for analyzing
anisotropic thermal transport properties of the top part of
a wafer material, by probing a region between the top sur-
facedown to a depth of <50 μm. To verify the technique,
i.e., investigate the accuracy and precision, a series of mea-
surements were performed on a 500-μm-thick y-cut single
crystal quartz wafer. By using a pulse transient recording
with square-shaped pulses of maximum length 70 μs and
duty cycle 5%, the thermal probing depth was limited to
~30 μm. The acquired average temperature increase in the
Hot Strip sensor versus pulse length was fitted to a theore-
tical model that assumes a slab sample of “finite” thickness,
and positioned on an “ideal” heat sink. From these fittings,
the thermal conductivity and thermal diffusivity tensors, and
volumetric specific heat, of single crystal quartz could be
determined with a precision better than 2.7%, and the ob-
tained average values agree well to literature values on the
 corresponding bulk properties.

As a remark, the Slab PTHS method does not exclude
the possibility of measuring the anisotropic thermal transport
properties of a crystalline thin film (<50 μm) deposited on
a substrate of different material, which is of high practical
importance in, e.g., the semiconductor industry. The condi-
tions for obtaining the “true” thermal transport properties of
the thin film are (a) to use a thermal probing depth of the tran-
sient recording that does not exceed the thickness of the thin
film, and (b) to ensure that a constant “background” temper-
perature (ΔTbg) between the Hot Strip sensor and the heat sink
(i.e., the bottom side of the substrate) has been established,
by using a certain minimum number of pulse periods in the
applied pulse trains. To overestimate the number of periods,
one could, for example, calculate f2(τbg) assuming the sam-
ple (i.e., substrate with thin film) has a thermal conductivity
which is the lowest of the (estimated) values for the substrate
or thin film. Finally, it should be noted that the thin film may
also consist of a multilayered material stack, in which case
the measured properties would be the effective thermal transport
properties over the thermal probing depth.

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