Determination of diminished thermal conductivity in silicon thin films using scanning thermoreflectance thermometry

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The variation of optical reflectance from silicon thin films in response to a change in temperature, i.e., the thermoreflectance, was used to monitor heat conduction processes within the films and confirm reduction of their in-plane thermal conductivity with decreasing film thickness. The measurements were also fit to numerical solutions of the heat conduction equation through which it was found that observed conductivity values were consistent with predictions based on phonon dispersion and phonon-boundary scattering considerations. The methods used may have practical implications for monitoring heat dissipation in silicon-on-insulator based microdevices. © 2010 American Institute of Physics. [doi:10.1063/1.3527966]

The study of heat dissipation in silicon thin films is important for insight into the effects of reduced dimensionality in thermal energy transport and also in many applications, e.g., for use as the device layer in silicon-on-insulator (SOI) structures in microelectronics for larger circuit density and superior device performance through reduced parasitic capacitances. The high refractive index contrast in SOI structures also enables wavelength-scale photonic integrated circuits. However, device performance could deteriorate due to poor heat dissipation from the diminished in-plane thermal conductivity, $\kappa_p$, of the silicon thin films in addition to the low thermal conductivity, $\kappa$, of the buried oxide (BOX). To probe such issues, many methods have been developed, none of which are completely satisfactory. For example, intrinsic ambiguity in the $\kappa$ values of the films, arise through use of resistance thermometry or the 3ω method due to electrical/thermal contact related issues. Consequently, noncontact optical methods, e.g., employing thermoreflectance (TR), are desirable.

In this context, time domain TR (Ref. 11) has been previously used to investigate thermal conductivity related issues and is based on heating the surface transiently through laser pulses. The lateral span of the initially heated region is of the order of the laser wavelength, $\sim 1-10 \mu m$ practically, while the transverse span would correspond to the optical skin depth, $\sim 50$ nm. Such large aspect ratio ensures that the resultant cross-plane heat transport is one-dimensional and was modeled as such. Through a subsequent time resolved measurement of the reflected radiation intensity, the thermal diffusivity could be obtained. Since heat transport perpendicular to the film surface in SOI structures is generally constrained by the BOX, it would be instructive and necessary to also measure the in-plane $\kappa$ of the thin films and is the topic examined in this paper. We then demonstrate and model a scanning TR method for the determination of the $\kappa_p$ of Si thin films with thicknesses in the range of $\sim 68-258$ nm. We observed a drastic reduction in the $\kappa_p$ with decreasing thickness, which was understood through a consideration of the phonon dispersion in silicon in addition to phonon-boundary scattering.

For the fabrication of Si films of varying thickness, a SOI wafer (from SOITEC S.A., Bernin, France), with a top Si single crystal device layer, p-type and (100) oriented, of thickness $258 \pm 0.5$ nm, a buried oxide layer thickness of $1 \mu m$, on a Si substrate of $\sim 675 \mu m$ was chosen, Fig. 1(b). Reactive ion etching of the device layer was used for producing lower film thicknesses. Metal lines (8–90 $\mu m$ wide and 4–12 mm long) comprising Cr (10 nm)/Au (200 nm) were then deposited by electron-beam evaporation on the surface and used for resistive heating of the films. With reference to the cross section of the sample, the $\sim 8$ $\mu m$ heaters may behave more like point sources of heat while at larger widths, $\sim 90 \mu m$, the cross-plane heat flow would be probed. Enunciating the principle of our measurement, a

![FIG. 1. (Color online) (a) Outline of experimental apparatus, for gauging the in-plane thermal conductivity ($\kappa_p$) of the Si thin films, through scanning thermoreflectance thermometry, (b) Schematic of the sample cross section, indicating the Si thin film device layer, BOX layer, and the underlying Si substrate (handle) with calculated temperature profile (from resistive heating through the Cr/Au metal lines) corresponding to the area in the dotted box. In the profile, the light blue contours indicate isotherms at each 0.05 K increment.](http://apl.aip.org/apl/FIG.png)
temperature change, $\Delta T$, due to the film heating would lead
to a variation of the refractive index and consequently cause
a change in the optical reflectance$^{13}$ at the interface. For
small temperature variations, the relative reflectance change

$$\frac{\Delta R}{R} \sim \frac{1}{R} \frac{dR}{dT} \Delta T$$
can be monitored, as indicated through Fig. 1(a).

In the experiment, linearly polarized light from a He–Ne
laser ($\lambda=632.8$ nm, 10 mW) was circularly polarized by a
quarter wave plate and focused normally to a spot radius of
$\sim 3 \mu m$ through a reflecting objective lens (Ealing, Rocklin,
CA) $36\times$, Numerical Aperture=0.5, onto the device layer.
The films were then heated by passing a sinusoidal current of
frequency $f$, from a current source (6221: Keithley Instru-
ments, Cleveland, OH), through the metal lines, which then
produces a heating pulse at $2f$ due to Joule heating. The
heated sample was then scanned underneath the beam, away
from the heater, while the reflected beam was diverted
through a nonpolarized beam splitter. The reflected beam sig-
nal was transduced into a current by the photodetector
DET110A, (from Thorlabs, Newton, NJ), subsequently am-
plified using a current preamplifier SR570 (from Stanford
Research Systems, Sunnyvale, CA), and then measured
through a lock-in amplifier (Stanford Research Systems
SR830) tuned to the reference frequency of $2f$. The dynamic
reserve of the lock-in amplifier was $\sim 120$ dB and enables
measurement up to the noise limit of the photodetector,
yielding $\Delta R/R \sim 10^{-6}$. The $f$ was chosen to be $\sim 2.5$ kHz,
so that convective heating effects could be minimized and
ignored. Additionally, an overall low measurement tempera-
ture mitigates radiative heat loss. At the chosen $f$, the thermal
penetration depth$^{13}$ ($=\sqrt{\kappa/2\pi f \rho C}$, for a given density, $\rho$, and
specific heat, $C$, of the sample) is $\sim 75 \mu m$, assuming bulk
Si values ($\kappa_{Si}=148$ W/m$\cdot$K, $\rho_{Si}=2329$ kg/m$^3$, $C_{Si} \sim 1.67$
$\times 10^4$ J/m$^3$K$^{-1}$) and corresponds to heat spreading under-
neath the metal lines [see Fig. 1(b)]. This figure indicates
results from a two-dimensional finite element model (COMSOL$^0$, COMSOL, Inc., Los Angeles, CA) near the peak
of the heating cycle, from the time-dependent temperature
distribution along the sample cross section with incorporated
parameters including the cross-plane thermal boundary con-
ductance, $h_i$, input heating power, $P$, heating frequency, $f$,
heater width, $w$, etc.

It was seen through such simulations that the highest
temperature drop occurs over the BOX layer due to its low $\kappa$
and that the thermal boundary resistance at the layer inter-
faces does not significantly modify heat flow. A representa-
tive, experimentally observed variation of the TR signal
$\Delta R/R$ along the surface of the silicon device layer is shown
in Fig. 2. Each datum represents the averaged TR intensity
over the width of the focused beam, $\sim 6 \mu m$, centered at
the specified point. To evaluate the difference between the mea-
sured and actual temperature, a finite element model based
distribution was used to find the averaged temperature over
the width of the beam, which was compared to the modeled
temperature at the center of the beam. The difference be-
tween the two values was found to be less than 2% implying
that error due to the inherent averaging in the measurement
was negligible. It was also obvious from such measured pro-
files that an exponential dependence, typical of one-
dimensional heat flow,$^{13}$ would not exactly fit possibly due to
cross-plane heat transfer in addition to lateral thermal trans-
port along the device layer.

A quantitative determination of the $\kappa_{ip}$ for the silicon
device layer requires a robust correlation between the mea-
sured $\Delta R$ and calculated $\Delta T$. At $\lambda=633$ nm, the electromag-
netic skin depth is $\sim 2.29 \mu m$ (given that the complex index
of refraction, at room temperature, for Si and SiO$_2$ is
$=3.92+0.022i$ and $=1.457$, respectively)$^{14}$ and implies that
the light probe penetrates both the device and the BOX lay-
ers. The contribution to $\Delta R$ would then arise from a modified
reflectance due to a temperature induced refractive index
change ($dn/dT$) of the individual layers, i.e., considering
both Si,$^{15}-(4.5+0.73i) \times 10^{-4}$ K$^{-1}$, and amorphous$^{16}$ SiO$_2$,
$\sim 10^{-5}$ K$^{-1}$. An appropriate optical transfer function$^{17}$ was
then constructed to model the total $\Delta R$.

It was seen through such modeling that the temperature
variation of reflectance for the oxide layer could be orders of
magnitude smaller compared to that for the silicon device
layer, through dependence on the device layer thickness, and
could affect the $\Delta R$. From the modeled temperature profiles,

![Figure 2](image_url)

*FIG. 2. (Color online) A typical normalized TR scan of a sample with a 235
nm device layer as a function of distance (x) from the heater edge. Calculated
fits of the in-plane thermal conductivity, $\kappa_{ip}$, comparing bulk ($\sim 148$ W/m$\cdot$K) and predicted values ($\sim 100$ W/m$\cdot$K) are shown. The inset
shows a representative range of $\kappa_{ip}$, that best fits data and approximately
indicates the error ($\pm 15$ W/m$\cdot$K) in the fitting of the $\kappa$.\*
tional analysis assuming that all the phonons (both acoustic and optical) contribute to the thermal conductivity (the “gray” approximation) typically yields a mean free path ($l_{\text{mfp}}$) of ~41 nm (using the bulk values of the specific heat capacity, $C_s \sim 1.67 \times 10^6$ J/m$^3$ K and sound velocity, $v_S \sim 6.4 \times 10^3$ m/s) and suggests a reduced $\kappa$ for film thicknesses less than ~40 nm. However, we considered, in addition to phonon-boundary scattering, (a) the complete phonon dispersion in silicon,\textsuperscript{19} (b) that only the acoustic phonons contribute, while the optical phonons do not contribute due to their small group velocity, and (c) that the specific heat capacity and velocity would be those appropriate for acoustic phonons, i.e., $C_s \sim 0.95 \times 10^6$ J/m$^3$ K and $v_S \sim 2.3 \times 10^3$ m/s. We then deduced a modified $l_{\text{mfp}}$ of ~200 nm, with an implication of a reduced $\kappa_{\text{film}}$ at film thicknesses in this regime. The results of such modeling are indicated as dashed lines in Fig. 3, where good agreement of the experimental data with the modified $l_{\text{mfp}}$ was observed.

In summary, we have shown that the determination of optical reflectance from thin silicon layers could be used to gauge their in-plane thermal conductivity and understand lateral thermal energy transport. The accordance of experimental results with numerical simulations and theoretical models validates the proposed methodology.

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