Wavelength-modulated interferometric thermometry for improved substrate temperature measurement

K. L. Saenger, F. Tong, J. S. Logan, and W. M. Holber
Thomas J. Watson Research Center, IBM Research Division, Yorktown Heights, New York 10598
(Received 3 October 1991; accepted for publication 29 April 1992)

Interferometric thermometry is a promising noncontact technique for measuring the temperature of transparent substrates (with polished front and back surfaces) from thermally induced changes in sample thickness and refractive index. However, for substrates of uniform thickness, the technique is not sensitive to the direction of temperature change, thus restricting its use to situations in which the temperature variation is monotonic. In this paper, we present some new schemes for interferometric thermometry based on the wavelength modulation capabilities of the distributed feedback laser diode. These schemes allow both the magnitude and direction of temperature change to be determined. One scheme utilizes to measure temperature changes in a silicon wafer during thermal cycling is described in detail. In addition, the calibration factors required to convert the thermally induced reflectance oscillations ("fringes") of known-thickness samples into temperature change are provided for Si and GaAs at wavelengths near 1.3 μm.

I. INTRODUCTION

Substrate temperature is increasingly being recognized as an important processing parameter in the fabrication of a wide variety of thin-film materials and devices, particularly in the microelectronics industry. This fact has prompted a renewed interest in the application of interferometric thermometry (IT) techniques for temperature measurement. A variant of a thermometry method first used in the 1920s and 30s, this noncontact optical technique utilizes interferometry to determine temperature changes from the thermal expansion and refractive index changes of a transparent substrate of known thickness whose front and back faces are polished and approximately parallel. Temperature changes are measured by counting oscillations (fringes) in the reflectance signal; for substrates with thicknesses of order 1 mm, one fringe typically corresponds to a temperature change of 3–50°C, depending on the material and probe wavelength. Substrate materials recently investigated with this technique include a number of optically transparent dielectrics, for which a red HeNe laser at 632 nm was used, and several optically absorbing semiconducting materials such as Si and GaAs for which IR lasers at 1.15, 1.5, 3.4, and 3.39 μm were used.

Interferometric thermometry is well suited to measurements both near and above room temperature and, in contrast to pyrometry techniques, to cryogenic measurements as well. The maximum temperature accessible with IT is limited only by the thermal and chemical stability of the substrate material and the requirement that the material remain transparent at the probe wavelength λ. For several dielectric materials, measurement capability has been demonstrated up to ±900°C. In agreement with predictions, band-gap absorption limits measurements on undoped or lightly doped Si (with sample thicknesses of order 600 μm) to ±350°C for λ=1.15 μm (Ref. 6) and, as verified in the present work, to ±750–800°C for λ=1.52 μm.

For a number of reasons, IT has remained more of a laboratory curiosity than a mainstream thermometry technique. One reason is that the technique is restricted to samples with polished front and back faces. However, the use of substrates meeting these requirements is becoming more common in many areas of the semiconductor industry. The requirement that the sample’s initial thickness and temperature be known is an additional, although usually minor, inconvenience. The major drawback of IT in its present form is that, for samples of uniform thickness, it is not sensitive to the direction of temperature change. As a consequence, temperature changes must be monotonic for unambiguous counting of the fringes.

In this paper, we present several related schemes for IT which utilize the wavelength modulation capabilities of commercially available distributed feedback diode lasers to determine both the magnitude and direction of temperature change. With these schemes, IT can be used to monitor highly nonmonotonic temperature changes, opening up important applications such as temperature control (where the temperature can be expected to oscillate around a set point). After reviewing the basic features of IT, we will outline some older approaches to the problem of determining the direction of temperature change. The remainder of the paper will focus on three new wavelength modulation schemes we have developed, one of which will be described in detail.

II. PRINCIPLES AND PRACTICE OF INTERFEROMETRIC THERMOMETRY FOR MEASUREMENT OF MONOTONIC TEMPERATURE CHANGES

A. Fundamentals

A good introduction to laser interferometric thermometry can be found in two recent papers. In essence, the technique is based on the fact that changes in the temperature of a slab of transparent material with optically
smooth, parallel faces can be quantitatively determined from changes in the slab's reflectance (at a given wavelength) due to changes in the temperature-dependent optical path length difference between interfering reflections from the slab's front and back surfaces. The slab (or temperature sensor) can be a substrate or thin film and the reflectance is typically measured at normal incidence with a low-power probe laser.

The reflectance of a nonabsorbing temperature sensor, such as that shown in Fig. 1, to normally incident light of wavelength \( \lambda \) is given by

\[
R = \frac{2r^2(1 - r^2 \cos \phi)}{1 - 2r^2 \cos \phi + r^4}.
\]  

(1)

The Fresnel reflection coefficient \( r \) is defined as \( r = \frac{(n_0 - n)}{(n_0 + n)} \), where \( n_0 \) and \( n \) are the respective refractive indices of the material surrounding the sensor (typically air), and the sensor material itself. The term

\[
\phi = \frac{2\pi}{\lambda}(2nL)
\]  

(2)

is the phase difference between the reflections from the front and back surfaces; it is \( 2\pi/\lambda \) times the optical path length difference \( 2nL \) due to a round trip through the temperature sensor, with \( L \) being the sensor's thickness. For light incident on the film at angle \( \theta \) (with respect to the film's normal), the term \( nL \) in Eq. (2) is replaced by \( L \sqrt{n^2 - n_0^2 \sin^2 \theta} \).

Changing \( \phi \) by \( 2\pi \) will take the reflectance \( R \) through one complete oscillation, referred to as a "fringe." For convenience, phase changes are expressed in terms of fringes \( \Delta F \), where \( \Delta F = (\phi - \phi_i)/2\pi \) and \( \phi_i \) is the initial phase.

For a substrate at uniform temperature \( T \),

\[
\frac{d\phi}{dT} = \frac{2\pi}{\lambda} 2nL(\alpha + \beta),
\]  

(3)

where \( \alpha \equiv (1/L)(dL/dT) \) is the substrate's thermal coefficient of linear expansion, and \( \beta \equiv (1/n)(dn/dT) \) is the relative temperature coefficient of the substrate's refractive index. The calibration factor \( \Delta T/\text{fringe} \) is simply

\[
\Delta T/\text{fringe} = \left( \frac{d\phi}{dT} \right)^{-1} = \frac{\lambda}{2\pi nL(\alpha + \beta)}.
\]  

(4)

It is clear from Eq. (4) for \( \Delta T/\text{fringe} \) that several factors affect the temperature sensitivity (i.e., the fringes per degree of temperature change) of a given temperature sensor or substrate. For a given material, the thicker the substrate, the greater its sensitivity. The dependence of the sensitivity on \( \lambda \) arises directly from the explicit factor shown in Eq. (4), as well as indirectly from the dependence of \( \alpha \) and \( \beta \) on \( \lambda \). The dependence of \( \Delta T/\text{fringe} \) on the sum of \( \alpha \) and \( \beta \) implies that sensitive thermometers need not be restricted to materials with large thermal expansion coefficients. For example, silicon has a small coefficient of thermal expansion (\( \alpha_{Si} = 3.5 \times 10^{-6}/\text{C} \)) but is a sensitive sensor material due to its large thermal coefficient of refractive index (\( \beta_{Si} \approx 5 \times 10^{-5}/\text{C} \) at \( \lambda = 1.5 \mu \text{m} \)).

D. Practical aspects of temperature measurement with interferometric thermometry

In temperature measurement with IT, the final substrate temperature \( T_f \) is given by its initial temperature \( T_i \) plus (or minus) the temperature change \( \Delta T \) determined from \( \Delta F_{obs} \), the number of fringes observed during monotonic heating (or monotonic cooling). When the heating or cooling is not monotonic, \( \Delta F_{obs} \) is the cumulative phase change in units of fringes, i.e., the number of fringes that would be observed if the temperature changed from \( T_i \) to \( T_f \) monotonically. The relationship between \( \Delta F_{obs} \) and \( \Delta T = T_f - T_i \) can be determined if the \( \Delta T/\text{fringe} \) factor of Eq. (4) is known over the temperature range of interest. Typically, \( \Delta T/\text{fringe} \) decreases with increasing temperature; for silicon, \( \Delta T/\text{fringe} \) decreases by about 30% between room temperature and 600°C. Thus \( \Delta F_{obs} = \Delta T (T_f - T_i) \), the number of fringes observed during a monotonic change in temperature from \( T_i \) to \( T_f \) depends on \( T_f \) as well as \( \Delta T \).

The dependence of \( \Delta F(T; T_0) \) on \( T \) and \( T_0 \) can be expressed as a polynomial,

\[
\Delta F(T; T_0) = L_0[a_1(T - T_0) + a_2(T - T_0)^2 + a_3(T - T_0)^3],
\]  

(5)

where \( L_0 \) is the initial substrate thickness in \( \mu \text{m} \), and \( a_m \) \((m=1-3)\) are fitting constants determined for the particular reference temperature \( T_0 \) used in the calibration.

Equation (5) can be inverted to give \( T \) as a function of \( \Delta F \):

\[
T(\Delta F) - T_0 = b_1(\Delta F/L_0) + b_2(\Delta F/L_0)^2 + b_3(\Delta F/L_0)^3,
\]  

(6)

where \( b_m \) \((m=1-3)\) are again fitting constants determined for the particular reference temperature \( T_0 \) used in the calibration. The \( a_m \) and \( b_m \) depend on the material and \( \lambda \) but are independent of the...
The nonlinearities of Eqs. (5) and (6) require an algorithm such as the one given below for finding the substrate’s final temperature $T_f$ from $T_0$ and $\Delta F_{\text{obs}}$.

1. Use Eq. (5) with $T = T_f$ to find $\Delta F_i = \Delta F(T_f, T_0)$, the number of fringes that would have been observed if the sample temperature was changed monotonically from $T_0$ to $T_f$.

2. Use Eq. (6) with $\Delta F = \Delta F_f = \Delta F(T_f, T_0)$ = $\Delta F_f(T_f, T_0) + \Delta F_f(T_f, T_0) = \Delta F_{\text{obs}} + \Delta F_f$ to find $T_f = T_f(\Delta F_f)$. [Note that the term $\Delta F(T_f, T_0)$ is the number of fringes that would be observed if the sample temperature was changed monotonically from $T_0$ to $T_f$.]

The constants $a_m$ and $b_m$ for Si and GaAs were determined from fringe versus temperature calibration data for samples of known thickness. Data taken at the $\lambda = 1.523$ $\mu$m HeNe laser wavelength are shown in Fig. 2 for a silicon (p type, 11–25 $\Omega$ cm) sample heated in a tube furnace under flowing dry nitrogen. The samples were sandwiched between molybdenum blocks; sample temperature was measured with a thermocouple inserted into one block. A mechanically chopped laser output and lock-in detection were utilized for measurements between 700 and 800°C. This additional sensitivity was needed at high temperature to compensate for the smaller interference signal (decreased due to sample absorption effects) and larger background of blackbody radiation.

Table I gives the values of $a_m$, $b_m$, and $T_0$ obtained from calibration data for Si and semi-insulating GaAs, along with the room-temperature values of $\Delta T$/fringe for wafers of 0.05 cm in thickness. The values of the $a_m$ and $b_m$ at wavelengths $\lambda$ near $\lambda_0 = 1.523$ $\mu$m can be estimated from $a_m(\lambda) = (\lambda_0/\lambda)a_m(\lambda_0)$ and $b_m(\lambda) = (\lambda/\lambda_0)^n b_m(\lambda_0)$. This result follows from Eqs. (4)–(6) and the fact that the fractional changes in $n$ and $\beta$ for a given wavelength change are much smaller than the fractional change in $\lambda$. The calibration factors for the 1.55 $\mu$m wavelength of the diode laser described below were estimated with these expressions for $a_m(\lambda)$ and $b_m(\lambda)$. The low-divergence HeNe laser was preferred over the fiber output of the diode laser for the calibration measurements since a usable reflectance signal could be obtained from samples tens of cm inside the furnace without the use of any focusing optics or optical elements placed inside the oven.

III. PREVIOUS SCHEMES FOR DETERMINING THE SIGN OF $\Delta T$

The fixed-wavelength interferometers of the sort described above are not sensitive to the direction of temperature change for samples of uniform thickness. For example, a reflectance trace resulting from two fringes of heating followed by two fringes of cooling is indistinguishable from one resulting from four fringes of heating if the turning point in temperature occurs at a reflectance minima or maxima. However, turning points in temperature occurring elsewhere in the reflectance trace are clearly detectable as kinks.

The earliest refraction thermometers were based on the wedge-shaped sensor design shown in Fig. 3, in which the sign of the temperature change was determined from the direction of fringe motion across a fiducial mark. This approach has also been proposed by Donnelly and McCaulley with preexisting substrate thickness nonuniformities replacing the wedge.

A two-position analogy to the wedge could also be employed. In this configuration, a second point on the sample with a different local thickness corresponding to an $1/4$ fringe difference in phase is simultaneously monitored. This thickness difference $\Delta L$ would be about

![FIG. 3. Schematic of wedge interferometer; top (a) and side (b) views. The dark bands (representing minima in reflectance) move in the direction shown during heating or cooling.](image-url)
FIG. 4. Si wafer temperature (solid line) and reflectance vs time during thermal cycling for two interference signals offset by a quarter-fringe difference in phase. Note the kink at the turning point in temperature.

\[(1/4)(\lambda/2n),\] i.e., \(\approx 500 \text{ Å}\) for a silicon wafer and \(\lambda = 1.5 \mu\text{m}\). A turning point in temperature would then always be detected as a kink in at least one of the reflectance traces, since both traces could never simultaneously be at a reflectance minimum or maximum. This is illustrated in Fig. 4.

However, this arrangement suffers from two limitations: (1) two spatially resolved measurements are required, and (2) while sensitive to changes in the sign of \(\delta T\), the actual sign of \(\delta T\) (i.e., whether heating or cooling is occurring) requires knowledge of the sign of the difference in sample thickness at the two observation points, or a preliminary measurement during which the sample temperature is changed in a known direction.

IV. WAVELENGTH MODULATION SCHEMES FOR DETERMINING THE SIGN OF \(\delta T\)

In contrast to interferometric schemes based on lasers with a fixed emission wavelength, the following schemes utilize the distinctive injection-modulation feature of semiconductor diode lasers to modulate the laser wavelength. Here we discuss two basic approaches previously disclosed by us in Ref. 9: (1) interferometric thermometry with wavelength derivative of reflectance, with (a) small wavelength deviation or (b) full fringe wavelength deviation, and (2) interferometric thermometry with alternating quarter-fringe-spaced wavelengths. After describing the concept and implementation for scheme (1a), we will outline the potential advantages and apparatus modifications required for employment of the alternative schemes (1b) and (2). In contrast to the two-position or wedge schemes discussed earlier, wavelength modulation schemes require data from only a single point on the wafer. In addition, the sign of \(\delta T\) is accessed via a well-controlled modulation of the laser wavelength, freeing the measurement from a dependence on pre-existing thickness gradients which may be poorly characterized and highly variable from sample to sample.

A. Interferometric thermometry with wavelength derivative of reflectance (scheme 1a)

1. Concept

In the "small wavelength deviation" approach (scheme 1a), the laser wavelength is modulated over a range \(\Delta \lambda\) corresponding to a small fraction of an interference fringe, i.e., \(\Delta \lambda < \lambda^2/2nL\). The magnitude of the resulting reflectance oscillations, i.e., the differential reflectance, is proportional to the derivative of the reflectance with respect to wavelength. This derivative in conjunction with the wavelength-averaged reflectance is sufficient for absolute determinations of arbitrarily varying temperatures, providing that the initial temperature and calibration factors are known. To see this, consider silicon, a material for which the optical path length difference increases with increasing temperature. When the wavelength-averaged reflectance \(R\) is increasing (decreasing) in time, the wavelength derivative of the reflectance, \(\frac{dR}{dt}\), will be negative (positive) if the wafer is heating, but negative (positive) if the wafer is cooling.

2. Apparatus

The experimental setup is shown in Fig. 5. An InGaAsP distributed feedback laser (Fujitsu FLD 150F1CJ) with single-frequency output at \(1.55 \mu\text{m}\) is wavelength-modulated by sinusoidal modulation of the 40 mA bias current (set at 1.4 times the lasing threshold) by about \(\pm 2\) mA at 1 kHz. The total wavelength range scanned is \(\approx 0.25 \text{ Å}\), which is 1/25 times the optical fringe spacing for a Si wafer of \(\approx 500 \mu\text{m}\) in thickness.

The single fiber output of the laser is fed to one branch of a Y-shaped fiber bundle. The Y-shaped bundle was constructed from two 600-μm-diam fiber bundles, the ends of which were epoxied together in a tube to form the common leg. The common leg is positioned perpendicular to the sample, with a 1 cm sample-to-fiber distance. The \(\approx 500 \mu\text{m}\) thick silicon wafer sample is mounted on a copper block which can be resistively heated or water cooled. A silicone heat sink compound (Dow Corning 340) is used for improved thermal contact.

The second branch of the Y-shaped fiber bundle directs the light reflected from the wafer to a germanium photodetector. The photodetector output is amplified (with a Melles Griot transimpedance amplifier) and then divided by a signal proportional to the laser intensity (in our case, the transimpedance-amplified output of a built-in photodetector on the laser). This is necessary in order to cancel out the changes in reflected intensity due to the modulation-current dependence of the incident laser intensity (\(\approx 15\%\)).
TABLE II. The sign of the counts generated during thermal cycling when R crosses $R_{\text{ref}}$, $A^+"-"$ ($-"+"$) sign corresponds to increasing (decreasing) temperature.

<table>
<thead>
<tr>
<th>$R'&lt;0$ (or $R'_{\text{min}}$)</th>
<th>$R'&gt;0$ (or $R'_{\text{max}}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{dR}{dT}&gt;0$</td>
<td>$-$</td>
</tr>
<tr>
<td>$\frac{dR}{dT}&lt;0$</td>
<td>$+$</td>
</tr>
</tbody>
</table>

variation over the wavelength range used). The ratioed signal (proportional to reflectance) is then split between one of the low-pass ($<10$ Hz) filtered inputs of a microcomputer-based A/D converter (for collection of the wavelength-averaged reflectance signal) and the input of a lock-in amplifier. The lock-in amplifier provides the amplitude and sign of the reflectance modulation, and its output (also fed into a low-pass filtered A/D converter) is proportional to the differential reflectance at the wavelength extremes which in turn is proportional to $R'$.

During thermal cycling, the temperature was measured at two closely spaced points near the center of the wafer with a “fluoroptic” fiber probe (Luxtron Corp., Mountain View, CA) and with interferometric thermometry. The fluoroptic probe was operated in the noncontact mode, with the phosphor dot painted directly on the front surface of the wafer. Alternatively, temperature data were sometimes recorded from a thermocouple attached to the copper block near the wafer edge. All data ($R$, $R'$, and $T$) were collected at a 10 Hz sampling rate. The digitized values of $R$ and $R'$ were subsequently analyzed with a computer-based algorithm (see below) to determine $\Delta F_{\text{obs}}$ by the cumulative phase change in units of fringes.

3. Algorithm

Arbitrarily varying wafer temperatures can be determined in real time from the monitored values of $R$ and $R'$ by applying the following algorithm. The algorithm utilizes the value of $R_{\text{ref}}$ defined by $R_{\text{ref}} = (R_{\text{max}} + R_{\text{min}})/2$, where $R_{\text{max}}$ and $R_{\text{min}}$ are the maximum and minimum values of the wavelength-averaged reflectance $R$ during the most recently completed reflectance cycle. Corresponding terminology is also used for $R'$, the wavelength derivative of $R$. In principle, $R_{\text{ref}}$ should be zero, although in practice, it may have a constant offset arising from electronic errors in ratioing. Counts are generated every time $R$ crosses $R_{\text{ref}}$ (i.e., twice per fringe when the temperature is varying monotonically). When a count is generated, $R'$ will be near either a maximum (i.e., $R'_{\text{max}}$) or minimum (i.e., $R'_{\text{min}}$) or a minimum (i.e., $R'_{\text{min}}$ and $R'_{\text{max}}$). The sign of the count is determined from the signs of $dR'/dT$ (the time derivative of $R$) and $R'$. Table II shows the sign of the counts for materials such as silicon, for which optical path length increases with temperature.

Alternative algorithms may work as well. For example, counts might be generated every time $R'$ crosses zero, with the sign of the count determined from the signs of $dR'/dT$ and $(R - R_{\text{ref}})$. This algorithm may be preferable if the value of $R_{\text{ref}}$ is initially unknown, since $R_{\text{ref}}$ can initially be taken as equal to the initial value of the reflectance, with a gradual update to its true value as more data are acquired. However, caution must be exercised if $R$ is initially near a minimum or maximum.

Both of these algorithms provide a running total of $\Delta F_{\text{obs}}$ accurate to within the worst case uncertainty of $\pm 1$ fringe (i.e., $\pm 1$ count at each end of the temperature scan). This corresponds to a temperature accuracy of $\pm 0.08^\circ$C for a 500-μm-thick Si wafer at $\lambda = 1.5$ μm. This accuracy could be improved by a factor of two by generating counts four times per fringe, i.e., each time $R'$ crosses 0, and each time $R$ crosses $R_{\text{ref}}$. Further improvements would require a more sophisticated interpolation between fringes.

4. Results

Figure 6 shows the (10-point) smoothed data for $R$, $R'$, and wafer temperature $T$ as a function of time during thermal cycling. The 10-point smoothing was introduced to remove isolated noise spikes (whose magnitude was typically 10% or less than the $R$ and $R'$ signal amplitudes) present in all three traces. Between noise spikes we estimate the signal-to-noise (S/N) ratio in the raw data to be better than 100:1. The front surface wafer temperature as measured by the fluoroptic probe is shown in the top frame of Fig. 6 (dotted curve). Shown in the same frame (as the stepped solid line) is the temperature determined with IT, computed with the algorithm of Table II and the wavelength-corrected calibration constants of Table I. The IT-measured temperature change during heating corresponds to 11 fringes, about 1 fringe ($\approx 8^\circ$C) higher than that measured fluoroptically. Some of the discrepancy can be attributed to the coarseness of the algorithm. The remainder is attributed to the combined effects of inaccuracies in sample thickness measurement, flaws in the fluoroptic probe calibration, and possible sensitivity of the IT interferometric thermometry.
calibration to wafer doping level. It should also be noted that the IT and flourotic measurements both indicated that the Si wafer was several tens of degrees colder than the heating block, whose temperature was measured with a thermocouple. This again indicates the desirability of using direct (sample based) measurements for determining true wafer temperature.

B. Alternative wavelength modulation schemes for interferometric thermometry

1. Interferometric thermometry with full fringe wavelength modulation (scheme 1b)

In this approach, the wavelength is modulated over a range corresponding to just over one interference fringe. The resulting reflectance signal is analyzed to provide the values of the reflectance minima and maxima, as well as the mean-wavelength values of the reflectance and its wavelength derivative. As discussed earlier, knowledge of the reflectance and its wavelength derivative should be sufficient for temperature determination. However, real time knowledge of the neighboring minimum and maximum reflectance values facilitates the implementation of algorithms for automated fringe counting. In addition, knowledge of the reflectance minima and maxima allows temperature changes corresponding to small (Δλ/2) fractions of an interference fringe to be determined by interpolation.

To implement this scheme, the wavelength is modulated for a total wavelength deviation Δλ of about \(\lambda^2/2nL\), i.e., \(\approx 7\text{ Å}\) for a Si wafer of \(\approx 500\text{ μm}\) thickness and \(\lambda = 1.5\text{ μm}\). After ratiometric processing, the reflected signal is digitized. The reflectance minima and maxima can then easily be determined for each wavelength cycle; the mean-wavelength reflectance and its derivative with respect to wavelength can be found from analysis of the data at the cycle midpoint. No lock-in amplifier is required.

Modulation over a wavelength range of \(\approx 7\text{ Å}\) can be accomplished by temperature tuning, i.e., by regulating the current into the laser's thermoelectric cooler. For our laser, this modulation is limited to frequencies below 0.5 Hz, a rate that is too low for many applications involving fast temperature change. However, this frequency limitation is not a fundamental one. Lasers with substantially higher modulation frequencies could be realized with a more optimized package design, although no such devices are as yet commercially available.

2. Interferometric thermometry with alternating quarter-fringe-spaced wavelengths (scheme 2)

This approach utilizes two laser wavelengths whose wavelength spacing corresponds to a quarter of an interference fringe. The reflected intensity at the two wavelengths is monitored to generate two traces, a quarter fringe apart in phase. As in the case of the single-wavelength, dual thickness interferometer illustrated in Fig. 4, a turning point in temperature occurs only if both traces show a turning point in reflectance.

To implement this scheme, the laser wavelength can again be thermally modulated to achieve a total wavelength deviation \(\Delta\lambda\) of about \((1/4)(\lambda^2/2nL)\), i.e., \(\approx 1.7\text{ Å}\) for a Si wafer of \(\approx 500\text{ μm}\) thickness and \(\lambda = 1.5\text{ μm}\). The reflected laser intensity can be split between two boxcar integrators, each set to read the reflected intensity at one of the wavelength extremes. The two signals are then proportional to the reflectance, since the time-averaged laser intensity at a particular wavelength is constant in time. However, in contrast to schemes (1a) and (1b), there is no need for normalization by the laser intensity since the signal magnitudes are never directly compared.

V. DISCUSSION

We have described several approaches to wavelength-modulated interferometric thermometry, and have utilized the simplest one (small wavelength modulation approach, scheme 1a) to measure the slowly varying temperature of a silicon wafer on a hot plate during a single thermal cycle. The particular cycle displayed in Fig. 6 was chosen to illustrate the detection of a temperature turning point at a maximum in reflectance, i.e., at a position where the presence of a turning point could not be determined by consideration of the reflectance data alone. Data for other thermal cycling runs (not shown) indicate that the fringe counting algorithm works reliably for temperature turning points occurring at any position in a reflectance cycle. Since no errors are introduced at temperature turning points, a trace with multiple turning points (e.g., one taken under conditions of oscillating temperature) will be no less accurate than one with a single turning point.

We have not yet explored this technique for applications in the area of rapid thermal processing. However, there is every indication that wavelength-modulated IT would perform well at high heating rates, given a high enough modulation frequency and fast enough electronics. A modulation frequency of \(10^4\) Hz with scheme 1a would easily support the measurement of temperatures changing at rates of up to \(10^4\) fringes/s (i.e., \(500-1000 \text{ °C/s}\) for \(\lambda = 1.5\text{ μm}\) and 500-μm-thick Si wafers), although this would require photodetector and divider circuits with \(0.1-1\text{ M}\Omega\) response bandwidths. Preliminary measurements at \(10^4\) Hz indicate that signal-to-noise ratios should not be a problem. However, it should also be noted that for these applications, the simpler fixed-wavelength IT scheme may be preferred, since they are adequate for the measurement of monotonically varying temperatures, and intrinsically faster.

The present unavailability of diode lasers capable of high-frequency temperature tuning restricts the more sophisticated IT scheme 1b to applications where sample reflectivity variations are slow. Such a case might be encountered with a substrate whose temperature is slowly oscillating around some fixed value. However, the real-time monitoring of \(R_{\text{min}}\) and \(R_{\text{max}}\) provided by scheme 1b is not really needed for well-behaved samples showing constant values of \(R_{\text{min}}\) and \(R_{\text{max}}\). For these situations, scheme
la would clearly be the approach of choice for direction-sensitive temperature measurement, due to its speed and simplicity.

In conclusion, we have demonstrated that the wavelength modulation capability of the distributed feedback laser diode can be used for interferometric thermometry under conditions in which both the magnitude and direction of temperature change are varying. Wavelength modulation approaches offer clear advantages over previously utilized two-position or wedge schemes, in that there is no requirement for (1) spatially resolved measurements, or (2) samples with pre-existing thickness nonuniformities.

ACKNOWLEDGMENTS

The authors are grateful for the technical assistance of D. F. Bowen, and the management support of F.T. by P. E. Green.