Real-time Optical Thermometry During Semiconductor Processing

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(Invited Paper)

***Abstract*—The optical techniques used to monitor the temperature of wafers during semiconductor processing are surveyed. The physical principles underlying each method are described. Applications of each optical diagnostic are presented, along with the strengths and weaknesses of the probe. Most of these optical diagnostics have been implemented in research reactors to monitor wafer temperature during one or several types of thin-film processing, such as molecular beam epitaxy, rapid thermal processing, and plasma etching. Pyrometry is the workhorse of noninvasive optical probes of temperature, although it needs supporting models and optical measurements to improve accuracy. Other optical thermometric wafer diagnostics are very promising and are being developed intensively, particularly reflection interferometry, transmission spectroscopy, and various interferometry methods that directly measure the thermal expansion of the wafer.**

I. Introduction

OPTICAL diagnostics are widely used to study and to monitor semiconductor thin-film processing [1]. They can be employed to probe the gas above the wafer, adsorbates on the surface, the film itself, and the wafer, as well as many critical process parameters. The most important process parameter in many steps in microelectronics processing is the wafer temperature. Monitoring and controlling wafer temperature and assessing temperature uniformity are essential because process rates are often very sensitive to temperature and because wafer heating, and consequently the wafer temperature, can change during a thin-film processing step.

This article surveys the progress in developing optical diagnostics that can be used to measure wafer temperature. These probes are all useful for process development, and several are potentially useful for real-time monitoring during manufacturing. There is great interest in optical thermometry because it is noninvasive, fast, and can be quite accurate. Optical spectroscopies can also be used to measure the temperature of the gas above the wafer during dry processing. While such measurements are important in process development, they are rarely of interest in real-time monitoring during manufacturing and will not be addressed here. Reference [1] can be consulted for a discussion of optical thermometry in the gas phase, and for further details on measuring wafer temperature.

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A critical comparison of optical probes for real-time measurements depends on many factors: the specific application, the current state of development of each probe, competitive nonoptical probes, probe adaptability to tools, and the cost of implementation and operation. Another factor is how the probe is expected to be accepted by industry. Though this is a somewhat nebulous consideration, it is vital to assess the likelihood that the manufacturing community can be convinced to actually use the diagnostic. Some of these factors are rapidly changing due to new breakthroughs in technology and newly recognized needs, and consequently assessment of these temperature probes can appear to be highly subjective. Though no critical comparison or absolute assessment of the optical diagnostics of temperature is attempted here, the limiting features of each probe are cited and their suitability for real-time control is briefly discussed.

"Conventional" temperature sensors have been reviewed in [2]–[6]. This includes most nonoptical methods, such as those involving thermocouples, and one optical probe, pyrometry. Some novel nonoptical temperature sensors are also being developed. For example, Degertekin *et al.* [7] have determined wafer temperature by measuring by the speed of acoustic waves in the wafer; the wave is directed to the wafer and retrieved from the wafer by quartz pins, upon which the wafer sits. An optical analog of this technique is presented below.

Section II surveys the need for temperature measurements in thin-film processing. The fundamental physical principles underlying each technique used for optical thermometry is discussed in Section III. Section IV briefly describes applications of the various optical diagnostics to the thermometry of thin-film processing, along with their strengths and weaknesses.

II. The Need for Thermometry in Thin-Film Processing

Most thin-film processes involve thermally activated steps. In many of these processes, the rate limiting step is kinetics-limited and not mass-transport-limited and it is therefore controlled by temperature. This dependence is usually exponential, with an activation energy $E_{\rm act}$ and an Arrhenius form:

$$k_r = A \exp -\frac{E_{\rm act}}{k_B T}. \tag{1}$$

Consequently small changes in the temperature T can severely affect the rate of the process. This is particularly true in deposition processes, such as chemical vapor deposition (CVD), and in rapid, high temperature processes, such as rapid thermal

processing (RTP). Using this Arrhenius form, the fractional change in layer thickness L (δL) deposited during CVD due to a change in temperature (δT) is $\delta L/L = (E_{\rm act}/k_B T)(\delta T/T)$. With $E_{\rm act} = 1.6$ eV, as in polysilicon CVD from silane, $E_{\rm act}/k_B T = 19$ at 700°C, which is typical of RTP-CVD conditions [8]. At this T, the temperature must be controlled within 0.25% (±2.5°C) to maintain the thickness within 5% of the targeted value. Moreover, such temperature uniformity is needed across the wafer. If the temperature is high by 40°C, as is not uncommon using uncalibrated pyrometry for thermometry, the deposited film can be twice the intended thickness. In discussing sensor needs during integrated circuit manufacturing, Moslehi *et al.* [9] and Barna *et al.* [10] have concluded that the control of wafer temperature is essential in virtually every fabrication step.

Anderson [6] has discussed the ranges of temperature operation needed for each thin-film process used in the semiconductor industry. He also critiqued temperature measurement technologies for real-time monitoring, emphasizing conventional, nonoptical methods. The operating temperature ranges of semiconductor manufacturing processes are listed in Table I. Anderson separately discussed the thermometric needs in low temperature (−150 to +60°C), "room" temperature (10–80°C), moderate temperature (80–200°C), intermediate temperature (200–600°C), and high temperature (550–1250°C) processes. Though many potential applications for optical diagnostics of temperature are in the last two categories (200–1250°C), there is also interest in the second and third regions (10–200°C). Thermocouples are commonly used in many applications, though the accuracy of thermocouples mounted in chucks depends on thermal contact and conduction. Because RF excitation is common in intermediate temperature processing (except for annealing in tube furnaces), the use of noncontact methods, rather than thermocouples, is suggested because of potential RF pickup. More conventional methods, such as pyrometry and the fluoroptic probe have other problems in this temperature range (see below).

Extremely tight control of wafer temperature is needed in rapid thermal processing to obtain reproducibility and to minimize slippage and warpage due to temperature nonuniformity [11]. RTP temperature sensors must have high precision, ~1–2°C, and fast response, ~30 ms –1 s, for closed-loop control. Real-time measurements must not involve contacting the wafer, because contact thermal sensors rely on conductive heat conduction, which is relatively slow, and are also a source of contamination. Peyton *et al.* [11] surveyed noncontact temperature measurements for rapid thermal processing, and compared the strengths of each process. They emphasized the use of single-wavelength optical pyrometry, which is commonly used in RTP even though the wafer emissivity is sometimes uncertain, and variations of conventional pyrometry, including dual-wavelength and ellipsometric pyrometries. They also addressed the availability and cost of several of these sensors. Peters [12] has surveyed the need for temperature measurements in RTP. Roozeboom and Parekh [13] and Roozeboom [14] have detailed technological developments in pyrometry that can improve thermometry in RTP reactors.

TABLE I
RANGES OF WAFER TEMPERATURE MEASUREMENTS IN SEMICONDUCTOR PROCESSING (ADAPTED FROM ANDERSON [6], WHO ALSO INCLUDED LOWER TEMPERATURE PROCESSES). ALL TEMPERATURES ARE IN °C

Process	Temperature range	Measurement specification (accuracy/resolution)
Resist development	18 - 25	±0.5/±0.1
Ion implanting	20 - 70	
Soft resist baking	80 - 120	±0.5/±0.1
Post exposure harden (UV flood)	120 - 190	±1/±0.1
HMDS ovens	25 - 200	±1/±1
Plasma etching	~ 200	±2.5/±0.1
Alloying (and annealing)	375 - 450	±0.5/±0.25
Sputtering (metals, etc.)	25 - 500	±3/±3
Plasma-assisted deposition	200 - 500	
Tungsten CVD (cold wall)	300 - 600	±3/±0.5
MBE	300 - 1000	
CVD (furnace)	525 - 800	±0.5/±0.25
Oxidation (and annealing)	800 - 950	±1/±0.5
HIPOX tubes	750 - 1000	±1/±0.1
Oxidation furnace	750 - 1100	±0.5/±0.25
RTP	500 - 1250	±0.8/<±0.5

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Another potential problem in lamp heated processes, such as MBE (molecular beam epitaxy) and RTP, is the changing absorption of lamp radiation by the wafer during the process; this can lead to undesired changes in the wafer temperature unless the lamp output is controlled to maintain constant temperature. For example, the wafer temperature can increase as a semiconductor film is deposited on a substrate when the film has a smaller band gap than the substrate [15], [16]. Moreover, the emissivity changes during such a deposition, which can greatly affect pyrometric measurements, as is detailed in [13] and [14], and in Section IV. These effects must be monitored and controlled.

Temperature measurements can be made either on the front side or rear surface of a wafer. Given the tool design, access to either side may be difficult. The "high cost of real estate" on the front side argues against dedicating a region on the front surface for measurements. Though in most processes the temperatures should be the same on both wafer surfaces, in pulsed processing there can be a small temperature drop across the thickness of the wafer.

Thermal sensors that contact the wafer, such as thermocouples, pose a serious potential source of contamination in microelectronics processing. Further, the thermal contact to the wafer may not be adequate or reproducible. Temperatures derived from noncontact methods, such as optically-based temperature sensors, do not have this sensitivity. Still, the optical determination of temperature is indirect; physical or optical parameters are directly determined and temperature must be inferred from these parameters.

A temperature diagnostic may be suitable for process analysis and development, but may not be useful for real-time monitoring and control because of high cost or lack of robustness. Some temperature probes are useful only for specific purposes, i.e., for specific materials (e.g., Si and not GaAs), in limited temperature ranges, for particular processes (e.g., that do not modify the surface, such as oxidizing, doping, roughening, or smoothing it), or for specific manufacturing tools (e.g., with a specific type of optical access).

Many of the temperature methods used in film processing are precise and reproducible, but are not accurate. For example, optical pyrometry depends on emissivity, which depends on the wafer conditions, and can give readings that are off by 100°C. With such precise, yet inaccurate, sensors of wafer temperature have a definite, though limited, value. This is illustrated by the application of pyrometry in assessing temperature uniformity. With such sensors, processes are tuned for that one tool with test wafers. The temperature measurements are repeatable for future runs in that one tool, but cannot be transferred to other similar tools at that or other locations, or to even slightly different processes. These temperature sensors are not useful for flexible or adaptive manufacturing. Improved accuracy would reduce the need for test wafers and improve technology transfer [6]. Further, while some temperature measurements determine an absolute value of temperature, others, such as reflection interferometry at one wavelength, measure temperature changes only; still, this suffices in many applications.

III. The Physical Basis of Optical Thermometry

Thermometry by pyrometry involves measuring the thermal distribution of photons (Planck's blackbody radiation law), often within a narrow wavelength band. The emissivity of the radiating structure strongly affects the determination of temperature and is itself a function of temperature through the temperature dependence of the optical parameters and thermal expansion.

Most other optical probes of the temperature of solids relate either directly or indirectly to the thermal excitation of phonons (i.e., lattice vibrations) (Bose–Einstein distribution) and lattice anharmonicity. One exception is the intraband (free carrier) excitation of electrons and holes (Fermi–Dirac distribution). With this latter mechanism, below-band-gap wafer absorption can monitor the thermal density of intrinsic conduction band electrons and valence band holes to determine temperature [17]–[19].

Thermal expansion is directly related to the phonon population because lattice vibrations cause the lattice constant to increase, since the interatomic forces that bind the lattice are anharmonic. The volume coefficient of thermal expansion $\beta_T (= 3\alpha_T)$ is related to other lattice parameters by

$$\beta_T = \frac{\gamma_{G\mathrm{th}} \kappa_T C_V}{V} = \frac{\gamma_{G\mathrm{th}} \kappa_S C_P}{V}, \tag{2}$$

where $\gamma_{G\mathrm{th}}$ is the thermodynamic Grüneisen function, κ is the compressibility at constant temperature (T) or entropy (S), C is the heat capacity at constant volume (V) or pressure (P), and V is the volume [20], [21]. The connection of thermal expansion with anharmonicity is through the Grüneisen function $\gamma_{G\mathrm{th}}$, which is a weighted average of the mode Grüneisen parameters $\gamma_G = -d \ln \omega_p / d \ln V$, where ω_p is the phonon frequency for a given mode.

Several optical probes sense the effect of thermal expansion only, such as speckle and optical diffraction interferometries and reflection microscopies. Many other optical diagnostics probe both the effects of thermal expansion (directly) and the dependence of optical properties on temperature, which themselves often depend on the phonon population and thermal expansion.

In equilibrium, material properties are functions of T, V (volume), and P (pressure), two of which, say T and V, can be considered independent variables. Since most thin-film processes occur at constant pressure, the temperature dependence of a property X (band gap energy, dielectric function, etc.) can be expressed as

$$\left(\frac{\partial X}{\partial T}\right)_P = \left(\frac{\partial X}{\partial T}\right)_V + \left(\frac{\partial X}{\partial V}\right)_T \left(\frac{\partial V}{\partial T}\right)_P \tag{3a}$$

$$= \left(\frac{\partial X}{\partial T}\right)_V + \beta_T V \left(\frac{\partial X}{\partial V}\right)_T$$

$$= \left(\frac{\partial X}{\partial T}\right)_V + \beta_T \left(\frac{\partial X}{\partial \ln V}\right)_T, \tag{3b}$$

where $\beta_T = (1/V)(\partial V/\partial T)_P$ is the volume coefficient of thermal expansion. So temperature can affect material parameters explicitly, with constant volume, and implicitly, by how the parameter is affected by volume changes through thermal expansion.

The optical properties of a material in the visible and ultraviolet are often characterized by the critical points (CP) in the dielectric function, including the fundamental band gap. These critical point energies of a semiconductor depend on temperature because of lattice vibrations. Four interactions are important: 1) thermal expansion, which changes the band gap through its dependence on lattice constant (volume), 2) smearing out of the periodic potential (Debye–Waller factor), 3) electron-phonon coupling in second-order perturbation causing mutual repulsion of intraband electronic states, i.e., the Fan terms for intraband coupling, and 4) the Fan terms for interband coupling [22]–[24]. The effect of thermal expansion corresponds to the implicit dependence in (3) (second term), and can be determined from the known dependence of the band gap on pressure (volume). It usually contributes to a relatively small fraction of the whole effect of the temperature change. The last three terms correspond to the explicit dependence [first term in (3)]. In many semiconductors these four terms cause the fundamental band gap to decrease with temperature, and to decrease linearly with T at high temperature.

This dependence of critical point energy on temperature is often modeled by using one of two expressions. The Varshni expression [25] is an empirical fit:

$$E(T) = E(0) - \frac{\alpha_v T^2}{T + \beta_v} \tag{4}$$

with the Varshni coefficients α_v and β_v, and the parameter $E(0)$ for each critical point. Another expression linearly includes the Bose–Einstein factor for phonon population, and so explicitly includes the electron-phonon interaction [26]:

$$E(T) = E_B - a_B\left(1 + \frac{2}{e^{\theta_B/T} - 1}\right) \tag{5}$$

with parameters E_B, the interaction strength a_B, and the mean frequency of phonons involved (in temperature units) θ_B.

These parameters have been determined by several groups. For example, Cardona and coworkers used ellipsometry to determine the CP parameters in (4) and (5) for critical points in Si [27], Ge [28], GaAs [26], InP [29], InSb [30], and GaP [31]. Shen *et al.* [32] and Shen [33] used photoreflectance to obtain these parameters for GaAs, GaAlAs, InP, and InGaAs.

Photoreflectance and ellipsometry are used to monitor critical energies to obtain the temperature. Other spectroscopies more specifically monitor features related to the fundamental band gap energies in direct gap semiconductors. Spectral analysis of photoluminescence gives the band gap, from which temperature can be determined, and analysis of the change in band-edge absorption in a wafer is a sensitive probe of temperature.

Below band-gap absorption is a temperature probe often used for indirect gap semiconductors, such as Si. Very near the gap, phonon-assisted absorption is very important. This is strongly affected by the thermal population of phonons and by this thermal shifting of the fundamental band gap. At even lower photon energies, free carrier absorption due to intrinsic and extrinsic carriers dominates. As mentioned earlier, the intrinsic carrier density is affected by temperature.

Changes in temperature affect the complex dielectric function $\tilde{\varepsilon}(\omega)$. This function can be modeled near a CP by using the critical point energies [(4) and (5)], transition amplitudes and broadening parameters; these latter two parameters also depend on temperature. Thermal expansion also affects the dielectric function because the density of oscillators changes with temperature. As in (5), the broadening factor can be been modeled by using a term that depends on phonon population:

$$\Gamma_E(T) = \Gamma_1 + \Gamma_0\left(1 + \frac{2}{e^{\theta_B/T} - 1}\right). \tag{6}$$

These temperature-dependent dielectric functions are used for thermometry by reflectometry from interfaces, reflection interferometry, and ellipsometry, usually at wavelengths where the measured optical parameter is particularly sensitive to temperature changes. These latter two methods are also strongly affected by thermal expansion of any films atop the substrate, because of the optical thickness of a layer with thickness d is $n(\lambda, T)\, d(T)$. (These parameters can depend on T, and have been measured for many semiconductors by using ellipsometry, photoreflectance, etc.) This broadening parameter is partly determined by relaxation processes. The temperature dependences of the intensity and the rate of decay of photoluminescence, which are affected by nonradiative relaxation processes, are monitored in fluorometric probing.

Using a more phenomenological model based on (3), Thomas [34] has modeled the temperature dependence of the complex index of refraction ($\tilde{\varepsilon} = n^2$) by using the Lorentz–Lorenz formula, finding

$$2n\frac{dn}{dT} = \frac{(n^2+2)(n^2-1)}{3\hat{\alpha}}\left(\frac{\partial\hat{\alpha}}{\partial T}\right)_V - (n^2+2)(n^2-1)\alpha_T\left[1 - \frac{V}{\hat{\alpha}}\left(\frac{\partial\hat{\alpha}}{\partial V}\right)_T\right], \tag{7}$$

where α_T is the linear coefficient of thermal expansion and $\hat{\alpha}$ is the electric polarizability. The first term describes how the polarizability depends explicitly on temperature, while the second term describes the effect of volume change due to thermal expansion and how the polarizability and density both depend on volume (3).

The connection of the thermal excitation of lattice vibrations to temperature is direct in vibrational Raman scattering in solids. References [35]–[38] shows that the phonon frequency of a given mode, which is the Raman shift, includes a term that depends on thermal expansion and one that depends on the thermal population of phonons in that optical mode and in lower energy, acoustic modes. This first term depends on anharmonicity within that mode, while the second term depends on anharmonicity that causes intermode coupling. The phonon linewidth [35]–[38] is derived from the phonon population and intermode coupling terms. The ratio of Stokes to anti-Stokes Raman scattering rates also depends on the phonon density, and therefore on temperature. As is seen in [39], it can also be sensitive to optical parameters.

The change of acoustic velocity with temperature is closely tied to properties of phonons because both are determined by elastic constants. Further, the acoustic velocity also depends on density, which varies inversely with volume and therefore decreases with increasing temperature.

IV. A Comparison of Optical Thermometry Probes

Many optical diagnostics can be used to measure wafer temperature. Most are noncontact and noninvasive. Their relative merits for use in feedback and control depend on many criteria. The probe must have the required accuracy and precision (Table I), measurement speed, and be insensitive to instrument alignment, calibration, and drifts. Ability to measure absolute temperature or only changes in temperature may be needed, along with the ability to probe temperature uniformity. The diagnostic should be well described by a model, which should be able to account for changes that occur on the wafer as the process ensues. Experimental considerations include insensitivity to external light, avoiding special preparation of the wafer (such as the fabrication of line or grating structures that could also mean a potential loss of wafer real estate), and the ability to probe the backside of the wafer (which can be more complicated when the backside is rough, as it usually is, or coated with films—silicon dioxide and nitride films are common on the backside during the processing of Si wafers). Other practical factors include low cost of ownership and upkeep, the ease of implementation in current and new-generation tools, small footprint (size), potential for turnkey operation, robustness, nonperturbative nature of the probe, and versatility to other processes, materials, and temperature ranges.

Narrow-band pyrometry (radiation thermometry) is widely used in the processing of silicon wafers, especially in RTP re-

actors, and is straightforward to implement [6], [11]–[14]. The measured wavelength band is chosen to maximize the collected thermal radiation, to minimize light from the lamps that heat the wafer, and to maximize transmission of thermal radiation through reactor windows. Measurement accuracy critically depends on knowing the correct value of the emissivity, which depends on the properties of the wafer, overlying films, and surface conditions [8], [13], [14], [40]–[43]. Supporting real-time optical measurements and accurate models of the surface structure can improve the accuracy greatly. Light guides internal to the reactor can be used for collection and calibration [44], [45]. Improved values of the emissivity can be determined by calculation [8], [40]–[43], modulation and ripple methods [43]–[45], reflectometry [46], [47], ellipsometry [48], dual-wavelength pyrometry [49], [50], combined pyrometric and reflection interferometry [51]–[53], and by clever choice of the measured wavelength band [54]. Pyrometry does not have sufficient accuracy in the lower temperature ranges for silicon wafer thermometry (<600°C) [55] because the wafer is transparent in the infrared regions that need to be measured. Thermal emission can also be used to determine the temperature of borophosphosilicate glass (BPSG) films [56]–[58].

Absorption measurements are gaining acceptance because of their low cost, high precision, and sometimes also high accuracy. Band-edge transmission measurements are performed on direct gap semiconductor wafers, such as GaAs [15], [59]–[62], and below-gap phonon-assisted and free carrier absorption (transmission) measurements are performed for indirect gap materials, such as Si [17]–[19], [63]. In the single-pass transmission geometry [15], [59], [60], access to the wafer on both sides is needed, while in "reflection" double-pass versions, with diffuse reflection from the roughened backside [61], [62], or specular reflection from the front side [63], access to only one side is necessary. Light from either an external source or the heating lamps is used for the transmission diagnostic. Corrections for wafer roughness may be needed with this probe when data from wafers polished on both sides are used for calibration.

Reflection interferometry is a simple, straightforward and inexpensive monitor of wafer temperature [64]–[77]. A new fringe appears whenever the temperature T changes by:

$$\Delta T/\text{fringe} = \frac{\lambda}{2nh(\alpha_T + \tilde{\beta})}, \tag{8}$$

where h is the wafer thickness, n is the refractive index, $\alpha_T = (1/h)(dh/dT)$ is the linear coefficient of thermal expansion, and $\tilde{\beta} = (1/n)(dn/dT)$; n, α_T, and $\tilde{\beta}$ can be functions of temperature. Reflection interferometry is also applicable at low temperatures, and can even be used with wafers that are rough on one side [71]. Using single-wavelength monitoring, fringes must be counted relative to a reference temperature. Temperature increases can be distinguished from decreases only by using special procedures [67], [72], [75]. Interference effects in other optical probes may be useful in determining temperature, as in pyrometric interferometry.

Reflectometry at the interface of a bare wafer is also a simple, yet sensitive optical thermometer [78], [79]. Measuring reflectance is practical when used in the comparison mode (optical bridge) [78], but is also sensitive to process-related changes on the surface. Reflection from a edge of the wafer that moves with thermal expansion, which is a form of interferometry, is another relatively inexpensive diagnostic [80]; it (only) determines the average wafer temperature.

Use of reflection ellipsometry to measure temperature can be based on changes in the optical dielectric function (thick films, bare wafer) and/or interference effects (films atop a wafer) [81]–[86]. It is wiser to make measurements based on how the dielectric function changes with temperature than to directly track the temperature-dependent shifts of the critical point energies, because the peaks are broad and the determination of the exact peak involves a careful fitting procedure (second derivatives, variations in the phase angle, etc.). Ellipsometry is very sensitive to model assumptions, such as the model of the surface and overlayers, and to instrument alignment and calibration. Though it is relatively expensive, it is being utilized increasingly for real-time measurements of film thickness and composition and should be used for thermometry if it is implemented on a tool anyway for these applications. Signal analysis can be fast enough for applications in RTP [85].

Photoreflectance (PR) tracks critical points (derivatives of the dielectric function) [87], while photoluminescence (PL) from wafers tracks emission from the fundamental band gap of direct gap semiconductors [88]–[92] and has been used *in situ* during MBE [92]. Both methods are greatly limited by strong thermal broadening at high temperatures.

Optical thermometers based on thermal expansion perform measurements relative to a reference temperature. They involve analyzing the thermal expansion: 1) of the wafer, as probed by reflection from the side of the wafer relative to a fixed external optical element [80], 2) of a grating on the wafer whose groove spacing is compared by diffraction to a reference grating from the interference of two lasers (optical diffraction (Moiré) interferometry) [93]–[95] or an external grating [96], 3) of the distance between two gratings fabricated on a wafer, as probed by the interference between beams diffracted from the gratings [97], and 4) of the distance between features on the roughened back side of the wafer (speckle interferometry) [98], [99]. These techniques are relatively inexpensive and accurate. Those that require special surface preparation, such as the fabrication of gratings, or that use valuable wafer real estate on the front of the wafer have disadvantages. Use of speckle interferometry is promising because it does not require special wafer preparation, has the advantage of being a backside measurement, and can be employed to map the temperature across the wafer. The above-cited probe of reflection from the edge of the wafer has the first two advantages [80]; however, it measures only the average wafer temperature.

Raman scattering has potentially high spatial resolution [100], [101] and can used without special surface preparation. It is relatively insensitive to transparent surface overlayers. However, since Raman signals are weak, efficient collection is needed, along with the rejection of background light. It is often difficult to obtain the large solid angles needed for efficient light collection within production tools. Raman measurements of temperature-dependent phonon frequencies are straightforward [100], [101] but require the determination

of the peak frequency, while measurements of Stokes/anti-Stokes intensities ratios [102] have a limited temperature range and require careful correction involving optical parameters (in absorbing media) [39]. Raman scattering is generally limited to semiconductors and insulators (not metals). Since the lasers and detection systems commonly employed in laboratory Raman scattering experiments are too expensive for real-time control, specialized systems must be designed to lower the cost of Raman thermometry.

Optical techniques can also be used to generate acoustic waves at one place on the wafer and detect them elsewhere on the wafer, thereby determining the temperature-dependent propagation time [103], [104]. Thermal wave spectroscopies also sense acoustic waves optically [105].

These cited methods probe the optical properties of the wafer. In contrast, optical emission from optically excited theromographic phosphors placed at the tip of a probe is analyzed in fluoroptic measurements [106]–[110]. Measurements track either the amplitude or the decay time of this emission, both of which depend on temperature through the rate of nonradiative relaxation. Tracking the decay time, which is the more common method, is accomplished by measuring the decay rate after pulsed excitation or by phase-shift analysis with modulated excitation [110]. In this thermometry, either the probe is in contact with the wafer, and then the temperature measurement is accurate but invasive (and can lead to contamination), or the probe does not make contact with the wafer, and then this method is less accurate [107]–[109]. Temperature measurement errors are reduced if the phosphor is painted on the surface [106], but this is not possible during production because it would produce contamination. Commercial probes can be operated up to 450°C [109].

V. Concluding Remarks

Most of these optical diagnostics have been implemented in research reactors to monitor wafer temperature during one or several thin-film processes, such as MBE, RTP, CVD, or plasma etching. Pyrometry is the workhorse of noninvasive optical probes of temperature. Coupling pyrometry with supporting models and optical measurements has attracted much interest because it can greatly improve accuracy. Other noninvasive optical thermometric diagnostics of the wafer are very promising and are being developed intensively, particularly reflection interferometry, transmission spectroscopy, and various interferometry methods that directly measure the thermal expansion of the wafer.

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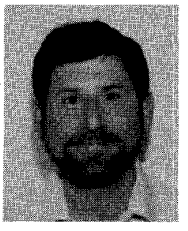

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