Some Recent Advances in Contactless Silicon Characterization

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Contactless measurements are attractive because they do not contaminate the sample and generally do not require extensive sample preparation. It is for these reasons that they are more commonly used. We will discuss mainly methods for material but some for device characterization and point out the advantages of these methods and also indicate their shortcomings.

### Introduction

Some contactless characterization techniques are shown here. A few of these are discussed in more detail.

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Some Techniques

Resistivity, Sheet Resistance, Doping Density

Induced Eddy Current/Microwave Reflection The inductively coupled or eddy current technique is based on a parallel resonant LC circuit. The $Q$ of such a circuit is reduced when a conducting material is brought close to the coil by the power absorbed by the conducting material. The oscillating magnetic field sets up eddy currents in the semiconductor leading to Joule heating of the material. The absorbed power is inversely proportional to the sheet resistance.1

The method is used for the measurement of sheet resistance and minority carrier lifetime. To determine the wafer resistivity the wafer thickness must be determined. Two methods are: differential capacitance probe and ultrasound.2 For lifetime determination, the time-dependent conductivity is measured. The eddy current technique is most commonly used during incoming inspection of silicon wafer resistivity and thickness and for the thickness measurement of highly conductive layers on less conductive substrates. The sheet resistance of the layer should be at least 100 times lower than the sheet resistance of the substrate to measure the layer and not the substrate. For example, the sheet resistance of a 5000 Å Al layer is about 0.06 to 0.1 ohms/square making such layers typically 1000 times less resistive than Si substrates. The sheet resistance yields the layer thickness with the layer resistivity from an independent measurement.

Capacitance-Voltage While doping profiling in polished wafers is not commonly done, profiling of epitaxial wafers is routinely carried out. With contactless techniques the wafer need not be sacrificed. A contactless capacitance measurement and doping profiling technique uses a contact held in close proximity to the semiconductor wafer. The sensor electrode, 1 mm diameter and coated with high dielectric strength thin film, is surrounded by an independently biased guard electrode. The sensor electrode is held above the wafer by a porous ceramic air bearing, which provides for a very stable distance from the wafer as long as the load on the air bearing does not change, shown in Fig. 1(a). The controlled load is provided by pressurizing a bellows. As air escapes through the porous surface, a cushion of air forms on the wafer that acts like a spring and prevents the contact from touching the wafer with the sensing contact floating approximately 0.5 $\mu$m above the wafer surface. The bellows acts to constrain the pressurized air and to raise the porous disk when the air pressure is reduced. If the air pressure fails, the disk moves up, rather than falling down to prevent wafer damage.3

The wafer is placed in a low-concentration ozone environment at about 450°C to reduce the surface charge on the wafer, especially critical for n-Si, to make it more uniform, and to reduce the surface generation velocity for deeper depletion.4 A recent comparison of epitaxial resistivity profiles by this contactless method with Hg-probe C-V measurements compared very favorably.5 The capacitance of the air gap is measured by biasing the semiconductor surface in accumulation. Light is used to collapse any possible space-charge region due to surface charge while the sensor is lowered and while the air gap modulation due to the electrostatic attraction is determined to eliminate any series space-charge capacitance. The capacitance of the air gap is the measured capacitance at its maximum value. The doping density profile is determined from conventional C-V expressions.12 Figure 1 shows a doping density profile and a contour plot of a $p$-type Si epitaxial layer on a $p^+$ substrate.
Sheet resistance is frequently measured with the four-point probe. The dose of ion-implanted samples is frequently determined by contactless modulated photoreflectance, which relies on detecting damage in the wafer. Probe penetration and junction leakage current are serious problems for ultra-shallow junctions, where it can lead to erroneous results. Modified contact techniques are the zero-penetration elastic metal four-point probe (EMP) and the micro four point probe (M4PP). EMP is a four-point probe with relatively large metal probes that make only elastic contacts leaving no imprints. M4PP uses a miniaturized four-point probe head made with a micro-machining process, allowing access to small structures. These methods do, however, make contact with the sample.
In the novel RsL non-contact sheet resistance and leakage current measurement technique, modulated, above band gap light illuminates the surface junction and creates electron-hole pairs. The internal photoelectron effect separates the carriers and they drift out of the region under the light beam, governed by the sheet resistance, $R_{sh}$, of the upper layer of the junction.

Two ac-coupled electrodes ~1 mm above the junction measure the spatial extent of carrier spreading. One electrode, $V_1$, is directly over the area, illuminated by the light beam, and the other, $V_2$, is a short distance away in the dark, shown in Fig. 2(a). The ratio of the junction photo-voltage signals collected by the two electrodes is determined by the junction sheet resistance, leakage current, and capacitance, which are separately determined in the RsL method. An RsL map is shown in Fig. 2(b).

Minority Carrier Lifetime, Defects

Surface photovoltage (SPV) is, of course, a well established technique. A major application of SPV is the measurement of iron in boron-doped silicon. The method relies on dissociating Fe-B pairs and measuring the minority carrier diffusion length before and after dissociation. Recent advancements allow determination of iron densities as low as $10^8$ cm$^{-3}$. The iron density is given by

$$N_{Fe} = 1.06 \times 10^{16} \left( \frac{1}{L_{nf}^2} - \frac{1}{L_{ni}^2} \right) \text{cm}^{-3}$$

where $L_{nf}$ and $L_{ni}$ are the final and initial diffusion lengths in μm. As the iron density in Si wafers decreases to $10^9$ cm$^{-3}$ and below, it becomes more difficult to determine $N_{Fe}$ for several reasons. The SPV analysis is generally based on the assumption that the sample be about $3L_n$ or more thick. This requires very thick samples with increasing diffusion lengths. For example, for $N_{Fe}=10^9$ cm$^{-3}$, $L_{ni} \approx 1000$ μm, requiring samples thicknesses of ~3 mm. Several precautions must be addressed for low iron density samples. The SPV signal decreases with decreasing $N_{Fe}$. The sample temperature must be accurately known as the optical absorption coefficient varies with temperature. Since the Fe-B pair dissociation is done by light flashes, it is important to keep these as short as possible not to change the sample temperature. The Si surface is sometimes treated with an HF-based solution to create a surface barrier to collect the minority carriers. This surface barrier changes with time and this influences the SPV signal. Interstitial iron formed by Fe-B dissociation, forms Fe-B again with the time constant

$$\tau_{pairing} = \frac{4.3 \times 10^5}{N_A} \exp \left( \frac{0.68}{kT} \right)$$

Obviously, the SPV measurements should be made before appreciable pair formation. Hence the measurement time after Fe-B dissociation and after surface treatment must be kept short. Signal averaging also helps for low-level signals. If all of these considerations are taken into account, it is possible to detect iron densities ~$10^8$ cm$^{-3}$ or even lower.

Quasi-Steady-State Photoconductance An important addition to the array of lifetime characterization techniques is quasi steady-state photoconductance (QSSPC). The sample is illuminated with a “slow” flash lamp with a decay time of several ms and an illumination area of several cm$^2$, which can be reduced to several mm$^2$ with a light pipe. Due to the slow decay time, the sample is under quasi steady-state conditions during the measurement. The steady-state condition is maintained as long as the flash lamp time constant is longer than the effective carrier recombination lifetime.
For a $p$-type semiconductor with steady state or transient light incident on the sample, the effective lifetime $\tau_{\text{eff}}$ is

$$\tau_{\text{eff}}(\Delta n) = \frac{\Delta n(t)}{G(t) - d\Delta n(t)/dt}$$

[3]

where $\Delta n(t)$ is the time-dependent excess minority carrier density and $G$ the ehp generation rate. The effective lifetime is given by\textsuperscript{12}

$$\frac{1}{\tau_{\text{eff}}} = \frac{1}{\tau_B} + D\beta^2 \tan\left(\frac{\beta d}{2}\right) = \frac{s_r}{\beta D}$$

[4]

where $\tau_B$ is the bulk recombination lifetime, $D$ the minority carrier diffusion constant under low injection level and the ambipolar diffusion constant under high injection, $s_r$ the surface recombination velocity, and $d$ the sample thickness. $\tau_{\text{eff}}$ is plotted in Fig. 3(a) versus $d$ as a function of $s_r$. For thin samples, $\tau_{\text{eff}}$ no longer bears any resemblance to $\tau_B$, the bulk lifetime, and is entirely dominated by surface recombination. The surface recombination velocity must be known to determine $\tau_B$ unambiguously unless the sample is sufficiently thick. For low to moderate $s_r$, Eq. [4] becomes

$$\frac{1}{\tau_{\text{eff}}} = \frac{1}{\tau_B} + \frac{1}{\tau_S}$$

[5]

where $\tau_S$ is the surface lifetime.

Figure 3. (a) Effective lifetime versus wafer thickness as a function of surface recombination velocity; (b) effective lifetime versus excess carrier density.\textsuperscript{13}

The QSSPC lifetime is shown in Fig. 3(b) as a function of injection level. As the injection level increases, the lifetime increases due to high-level injection and eventually decreases due to Auger recombination. The important point is that this measurement is done during one flash lamp decay and it yields information about the injection level dependence of the lifetime.

**Free carrier absorption** An interesting lifetime characterization approach uses infrared (IR) radiation from a black body transmitted through the sample and detected by an infrared light detecting array as the detector.\textsuperscript{14} The black body source can be as simple as a hot plate. A laser with photon energy $h\nu > E_G$ creates electron-hole pairs in the sample. By taking the difference of the IR radiation through the sample with and without the laser irradiation, one measures the free carrier absorption due to the excess carriers. Taking two-dimensional images of the IR radiation over the entire wafer simultaneously, allows for rapid measurements.
Knowing the laser generation rate $G'$ and the sample thickness $d$, the effective lifetime is

$$\tau_{\text{eff}} = \frac{d \Delta n}{G'}$$

where $G' = (1 - R) \Phi$, $R$ is the reflectivity and $\Phi$ the photon flux density. A two-dimensional lifetime map obtained in 50 s with this technique is shown in Fig. 4. No scanning is required, since both black body and excitation laser are broad area sources, covering the entire sample. The black body emits over a wide wavelength range. The peak wavelength occurs at

$$\lambda_{\text{peak}} \approx \frac{3000}{T} \mu m$$

A hot plate at $T=350$ K has its peak wavelength at $\lambda_{\text{peak}} \approx 8.6 \mu m$ - a very suitable wavelength for free carrier absorption measurements. Just as carriers absorb IR radiation, they also emit IR radiation. According to Kirchhoff’s law they emit the same power as they absorb to remain at a given temperature. Hence, if the black body source is absent, the sample itself will emit IR radiation and can be used to determine the lifetime. The sample is still excited with a laser and the difference signal is acquired as in the transmission system. Both emission and absorption have been used for lifetime measurements.\footnote{15}

Figure 4. Free carrier absorption minority carrier lifetimes of a multicrystalline Si wafer with 350 $\mu m$ lateral resolution. After Isenberg at al. ref. 14.

Photoluminescence (PL) has most commonly been used at low temperatures for impurity identification and for determining low doping densities ($N_{A,D} \leq 10^{12}$ cm$^{-3}$) in Si.\footnote{16} Recently, a PL-based new commercial tool, SiPHER, has been introduced, operating at room temperature with two wavelengths $\lambda = 532$ nm and 827 nm with optical penetration depths of 1.25 and 12.5 $\mu m$.\footnote{17} It measures PL and the reflectance and has found application to detect defects (dislocations, oxygen precipitates, metallic contamination) and doping density striations in silicon wafers.\footnote{18} Example PL maps and doping density striations are shown in Figs. 5-7, illustrating the versatility of the technique.

Figure 5 shows doping striations of an epitaxial layer on a heavily-doped substrate at the two wavelengths. The higher-wavelength, shorter-penetration depth light samples mainly the epi layer with quite uniform doping density. However, the lower-wavelength, higher-penetration depth measurement samples the substrate and clearly shows doping density striations. Figure 6 shows metallic contamination from an epitaxial deposition
and a dislocation micro-map of the same wafer. Figure 7 illustrates the effect of carrier diffusion, by comparing a PL map with a reflectance map clearly showing the Cu contaminated area. The PL map shows that incident light generated electron-hole pairs diffuse into the sample over a distance of about the minority carrier diffusion length $L_n$ and emit light when they recombine. The resolution of the measurement is determined by $L_n$.

Figure 5. Photoluminescence maps of an n-epi/n$^+$-substrate wafer. (a) $\lambda = 0.532 \ \mu m$, (b) $\lambda = 0.827 \ \mu m$. Data after A. Buczkowski, SUMCO.

Figure 6. Macro-map of 200mm blanket wafer showing metallic contamination from epitaxial process and micro-map of same wafer showing dislocations. Courtesy of T. Walker, Accent Optical Technologies.

Figure 7. Cu particle by (a) PL and (b) SR. Courtesy of T. Walker, Accent Optical Technologies.

PL has also been effectively used for SOI wafer characterization, where the wafers were irradiated with either the 351 and 364 nm UV lines of a cw Ar$^+$ laser or the 532 nm visible line of the second harmonic generation of a cw YVO$_4$ laser. The penetration depths of the two wavelengths are about 10 and 1250 nm, respectively. Since typical Si film thicknesses of SOI wafers are 100 nm or less and buried oxides are 100 to 300 nm thick, the shorter wavelength UV light samples the Si film and the longer wavelength the
substrate. Many wafers were sampled, of which Fig. 8 is one sample. The mapping patterns on the substrates were substantially different from one wafer to another, although they all exhibited concentric patterns, due to the oxygen precipitation striation in the Czochralski-grown Si crystals. The dark spots in Fig. 8(a) are due to bonding defects.

![Substrate Images](image)

**Figure 8.** 200 mm bonded SOI wafer. (a) UV excitation samples the Si film, (b) visible excitation samples the substrate. Maps courtesy of M. Tajima, Institute of Space and Astronautical Science, Japan.

**Optical Beam-Induced Resistance Change (OBIRCH)**

The optical beam-induced resistance change method has become an important failure analysis technique for integrated circuits. The chip under investigation is powered by applying the appropriate chip voltage and then it is scanned with all lines electrically active. Some of the laser energy is converted into heat leading to a temperature rise in the lines. The temperature coefficient of resistance (TCR) of metals is usually positive, so that a temperature increase leads to a line resistance increase and a current decrease, illustrated in Fig. 9(a).

![OBIRCH Diagram](image)

**Figure 9.** OBIRCH (a) schematic showing the incident laser from either top or bottom and the current change, (b) uniform metal line in dark with a defect ion the bright contrast area. After Nikawa ref. 22.

For constant voltage, the current change ($\Delta I$) due to the laser heating is approximately proportional to the resistance change ($\Delta R$), which is proportional to the temperature increase ($\Delta T$).\textsuperscript{20} When the laser beam scans, the heat is transmitted freely across defect-free areas, but heat transmission is impeded when the beam encounters defects, such as voids and Si nodules, creating differences in temperature increases between irradiated points.
that are near defects and those that are not. The resulting differences in $\Delta R_s$ are converted to $\Delta I$ or $\Delta V$ and displayed on a cathode ray tube in the form of brightness changes leading to failure analysis location determination.

A 1.3-µm laser ($h\nu < E_G$) does not generate electron-hole pairs in Si, i.e., it does not give an optical beam-induced current signal. For chips with multiple metal layers, OBIRCH images are observed by shining the 1.3-µm laser beam from the rear of a chip, because the 1.3 µm laser penetrates the Si substrate with about 40% power loss for moderately-doped Si about 500 µm thick. Materials with negative TCR include W (containing Ga), Ti (containing O) unintentionally left to be etched, and Ti-Al amorphous layers (containing O). The maximum temperature increase on the Al line is on the order of 10 K making the method nondestructive. To increase the resolution, OBIRCH has been combined with a near-field optical probe. The OBIRCH image in Fig. 9(b) shows a leakage current path as the dark contrast and the defective part as the bright contrast. FIB cross-sectioning the bright area for TEM observation revealed a short between Al lines. Subsequent energy-dispersive X-ray analysis showed the existence of Ti and O in that region with a negative temperature coefficient leading to the bright contrast in the OBIRCH image.

**Scanning Kelvin Probe Microscopy (SKPM)**

*Scanning Kelvin probe microscopy* falls in the category of *electrostatic force microscopy* (EFM) techniques. EFM can be divided into three regimes based on tip-sample separation: long range, intermediate, and short range. The SKPM probe, typically held 30-50 nm above the sample, is scanned across the surface and the potential is measured. Frequently this measurement is combined with atomic force microscopy (AFM) measurements. During the first AFM scan, the sample topography is measured and during the second scan, in the SKPM mode, the surface potential is determined.

The conducting probe and conducting substrate can be treated as a capacitor with the gap spacing being the spacing between probe and sample surface. A dc and ac voltage, applied to the tip leads to an oscillating electrostatic force between tip and sample from which the surface potential is determined. An advantage of force over current measurements is that the latter is proportional to the probe size while the former is independent of it. The frequency is chosen to be equal or close to the cantilever resonance frequency, which it typically around several 100 kHz.

For a dc and ac tip voltage, the force $F$ is

$$ F = \frac{1}{2} \frac{dC}{dz} \left[ (V_{dc} - V_{surf})^2 + \frac{1}{2} V_{dc}^2 (1 - \cos(2\omega t)) + 2(V_{dc} - V_{surf})V_{ac} \sin(\omega t) \right] $$

where $V_{surf}$ is the surface potential. $F$ consists of static, first harmonic, and second harmonic components. The relevant first harmonic is given by

$$ F_{oa} = \frac{dC}{dz} (V_{dc} - V_{surf})V_{ac} \sin(\omega t) $$

which becomes zero when $V_{dc} = V_{surf}$.

The method consists of applying an ac voltage of constant amplitude together with a dc voltage. A lock-in technique allows extraction of the first harmonic signal in the form of the first harmonic tip deflection proportional to $F_{oa}$. The oscillation amplitude is minimized by adjusting $V_{dc}$. A measure of the feedback voltage $V_{dc}$ is a measure of the surface potential. SKPM has also been combined with optical excitation.
Figure 10. AFM topographs, surface potential images, and surface potential profiles of GaN films 0.5, 1.1, and 14 µm thick. The grey scales correspond to 15 nm for the AFM and 0.1-0.2 V for the surface potential images. After Simpkins et al.26

Figure 11. (a) ZnO AFM surface topography. (b) SKPM image on grounded surface shows local work-function variations, under lateral (c) positive and (d) negative bias exhibit potential drops at grain boundaries. The direction of potential drops inverts with bias. After ref. 27.

Example AFM and SKPM plots are shown in Figs. 10 and 11. Figure 10 gives AFM, surface potential maps and surface potential line scans of GaN showing the effect of dislocations.26 Figure 11 is an effective illustration of surface potentials.27 The AFM topog-
raph (11(a)) exhibits no differences associated with multiple phases or grain boundaries in this ZnO sample. In the surface potential map with no external perturbation (11(b)), a depression of approximately 60 mV is observed due to the difference in work functions of the ZnO surface and pyrochlore phase. The surface potential map with the sample under applied lateral bias shows a potential drop at the grain boundaries in (c) and (d).

SKPM has the potential for high-resolution doping density profiling, because it measures the contact potential difference (CPD) that corresponds to the difference in the work functions between the tip and the sample. The work function, in turn, depends on the doping density. The difficulty thus far is correlating the SKPM signal to doping density.

**Stress**

**Raman Spectroscopy** When light is scattered from the surface of a sample, the scattered light is found to contain mainly wavelengths that were incident on the sample (Raleigh scattering) but also at different wavelengths at very low intensities (few parts per million or less) that represent an interaction of the incident light with the material. The interaction of the incident light with optical phonons is Raman scattering while the interaction with acoustic phonons results in Brillouin scattering. Optical phonons, with higher energies than acoustic phonons, give larger photon energy shifts. For example, the optical phonon energy in Si is about 0.067 eV, while the exciting photon energy is several eV (Ar laser light with λ = 488 nm has an energy of hν = 2.54 eV). If the incident photon imparts part of its energy to the lattice in the form of a phonon (phonon emission) it emerges as a lower-energy photon, known as Stokes-shifted scattering.

![Raman Spectra](image)

Figure 12. Raman spectra of Si and Si$_{1-x}$Ge$_x$/Si with x=0.15 to 0.4. Data courtesy of M. Canonico, Freescale Semiconductor.

Raman spectroscopy is sensitive to crystal structure, composition, stress, and temperature. Damage and structural imperfections induce scattering by the forbidden TO phonons, allowing implant damage to be monitored. The Stokes line shifts, broadens and becomes asymmetric for microcrystalline Si with grain sizes below 100 Å. The lines become very broad for amorphous semiconductors, allowing a distinction to be made between single crystal, polycrystalline, and amorphous materials. The frequency is also shifted by stress, as shown in Fig. 12, where the Raman spectra are shown for SiGe films grown on Si substrates. Due to lattice mismatch, such layers have built-in stress and can be used to create strained Si layers. Note the Si reference signal occurs at 1/λ ≈ 520 cm$^{-1}$ with the peak shifted to lower energies as the Ge fraction increases. Since the SiGe layers are usually very thin, the exciting laser must be absorbed within that layer, requiring a UV laser.
Polariscopy The optical properties of materials are in general functions of stress. In particular, the change of the refractive index of the material by the strain caused by the stress is called photoelasticity, which is widely used to determine distributions of stresses or strains in materials. When a stress is applied to an elastic medium, the produced strain is linearly related to stress. If a transparent material is optically isotropic in the absence of stress, the material becomes optically anisotropic by the application of a uniaxial stress, called photoelastically induced birefringence. The transmission of light in such anisotropic media has unique features not present in isotropic materials and can be used to determine the stress in the material.

When a uniaxial stress is uniformly applied to an optically isotropic material with the direction of the stress in the plane of the sheet, a plane-polarized light ray is broken up into two components - the ordinary wave and the extraordinary wave. These waves have polarization vectors at right angles to each other, corresponding to the principal stresses created by the uniaxial stress with different velocities. The ordinary wave has the polarization vector perpendicular to the direction of the uniaxial stress and the polarization vector of the extraordinary wave is parallel to the direction of the stress. Since the two components propagate with different velocities, a phase difference $\delta$ is produced between the two components upon emerging from the sheet that is proportional to the magnitude of the shear stress. The magnitude of $\delta$ can be observed by passing the emergent light through a second polarizing unit - the analyzer. The principal plane of the analyzer is usually placed at right angles to the polarizer.

The two wave components, upon emerging from the analyzer, are reduced into one plane and give rise to interference. When $\delta = (2m+1)\pi$, where $m$ is an arbitrary integer, constructive interference takes place and one may see the brightest field of view. When $\delta = 2m\pi$, the interference becomes destructive and the field becomes dark. In general, $\delta$ may take any value depending on the actual shear stress in the medium. If there is a distribution of stresses in a medium, bright and dark fringes are contours of equal shear stress. The magnitude of the shear stress can be calculated from the interference order of the fringes. When the polarization vector of the incident light is parallel to one of the principal stresses, the interference fringes disappear and the field of view becomes dark. Thus, the orientation of the principal stresses can be found by rotating the crossed polarizer and analyzer, allowing the distribution of the shearing stress to be determined.

![Figure 13. The (a) plane and (b) circular polariscope.](image-url)
Strain in semiconductors leads to birefringence (change in refractive index) resulting in a phase shift of transmitted light, that is proportional to the strain in the sample. Polariscopy is a nondestructive, highly sensitive and quantitative mapping technique for residual strains in semiconductor wafers, based on the strain-induced birefringence.\(^{30}\) The experimental arrangement for plane and circular polariscopes is schematically shown in Fig. 13. For transmission semiconductor stress measurements, light with \(h\nu < E_G\) is used. The infrared light passes through the polarizer and becomes circularly polarized. As light propagates through the silicon, residual stress-induced birefringence changes it from being circularly to elliptically polarized. The resulting phase shifts affect the polarization state of transmitted light waves. The intensity of polarization transmission is\(^{31}\)

\[
I_t = I_i (1 - R)^2 (\cos^2 \chi - \sin 2(\phi - \theta) \sin 2(\phi - \theta + \chi) \sin^2 \delta / 2) \quad [10]
\]

where \(I_i\) is the intensity of incident light, \(R\) the reflectivity, \(\theta\) the principal angle which determines the orientation of the stress axis at the plane, \(\chi\) the angle between polarizer and analyzer and \(\phi\) the azimuth angle of the polarizer, shown in Fig. 13. The polarization intensity \(I_t\) measured at selected orientations of the polarizer and analyzer, depends on the optical retardation parameter \(\delta\), which is directly related to the residual elastic strain. \(I_i\) is generally polarization dependent. Hence a method that does not require \(I_i\) and \(R\) is as follows. Two transmitted intensities of the polarized light are measured: one with polarizer and analyzer parallel to each other, \(I_\parallel (\chi = 0)\), and the second when the polarizer is orthogonal to the analyzer, \(I_\perp (\chi = \pi/2)\). By measuring the angular \(\phi\)-dependence of the current ratio one can determine quantitatively the optical retardation, \(\delta\), and the direction of the principal stress angle, \(\theta\), using the equation

\[
\frac{I_\perp}{I_\parallel + I_\perp} = \sin^2(\phi - \theta) \sin^2(\delta / 2) \quad [11]
\]

allowing stress to be determined. Example polariscopy images of stressed Si wafers are shown in Fig. 14.

![Figure 14](image-url)

Figure 14. (a) Residual stress in EFG Si wafer. Courtesy of S. Ostapenko, Univ. of South Florida, (b) stress induced by small crack in Si wafer. Courtesy of J. Lesniak, Stress Photonics.

**Temperature**

*Raman spectroscopy.* High spatial resolution temperature can be measured with Raman spectroscopy, since temperature changes the optical phonon energy leading to a shift in the scattered phonon’s energy, shown in Fig. 15. For Si the shift is \(-0.021\, \text{cm}^{-1}/\text{K}\). Fig. 16(a) shows the temperature along the width of a Si MOSFET clearly illustrating the non-uniform temperature distribution in the width direction.\(^{32}\) Fig. 16(b) shows the local
temperature near the drain-gate region of AlGaN/GaN power HFETs on sapphire and SiC substrates. The higher thermal conductivity of SiC clearly lowers the local device temperature and Raman allows such measurements to be made at high spatial resolution.

![Raman Shift (cm⁻¹) vs. Raman Intensity (a.u.)](image1)

Figure 15. MOSFET at $T = 25^\circ$C and 95°C. The 95°C peak is broadened and shifted to lower energies. Adapted from ref. 32.

![Temperature change profile and temperature versus power dissipation](image2)

Figure 16. (a) Temperature change profile along the Si MOSFET width direction (from ref. 32), (b) temperature versus power dissipation in the drain-gate region in AlGaN/GaN power HFETs (from ref. 33).

**Spectroscopic Ellipsometry (SE)**, a contactless, non-invasive technique measures changes in the polarization state of light reflected from a surface. One determines the complex reflection coefficient ratio $\rho$ which is dependent on the ratio of the complex reflection coefficient for light polarized parallel ($R_p$) and perpendicular ($R_s$) to the plane of incidence. Spectroscopic ellipsometric measurements have extended the range of conventional ellipsometry by using more than one wavelength. Furthermore, it is possible to vary not only the wavelength but also the angle of incidence, providing yet another degree of freedom. The ellipsometer is sensitive to surface changes on the order of a monolayer. Film thickness and alloy composition can be determined during growth or during etch. Optical measurements are ideal for real-time measurements because they are non-invasive and can be used in any transparent ambient including ambients associated, for example, with plasma processing and chemical vapor deposition.

**Film Thickness** Spectroscopic ellipsometry is one of few techniques allowing measurements of Si films of SOI wafers. Si films as thin as 10 nm can be reliably measured, as shown in Fig. 17, where strained Si on insulator (sSOI) substrates are fabricated by bond-
ing and layer transfer of strained Si layers from SiGe virtual substrates directly to oxidized handle wafers.\textsuperscript{35} In this process, the starting strained Si substrates utilize graded SiGe buffer technology to fabricate the high-quality relaxed SiGe template to introduce strain in the Si layer. Then, the strained Si wafers are bonded to a handle wafer with an intermediate oxide layer, and the strained Si layer is transferred by hydrogen-implant induced separation or grind and etch back. Ge contents of between 20\% and 30\% yield tensile Si strain levels between 0.8\% and 1.2\% and substrates are referred to as 20\% sSOI and 30\% sSOI, where the 20\% and 30\% refer to the approximate Ge content of the bulk strained Si substrates from which the strained Si layers were transferred. Spectroscopic ellipsometry coupled with Raman measurements allows thickness and strain to be determined.

Figure 17. A 10 nm, 20\% strain, sSOI strained Si thickness map. After ref. 35.

**Summary**

Contactless semiconductor characterization techniques are increasingly important. This trend is, of course, driven by the very nature of the techniques with no sample preparation. In many cases this leads to significant time and cost savings as sample preparation can be very time consuming. Such optical methods as ellipsometry and Raman spectroscopy have been used for many years, but recent demands of measuring very thin layers, e.g., SOI and strained Si, have expanded the methods by incorporating UV light excitation. Contactless carrier lifetime measurements are important as Si crystal quality has improved with time and lifetime is one parameter to characterize such wafers. It is also important to measure the lifetime in solar grade Si, where the spatial lifetime distributions are important and the new free carrier absorption method is very suitable for this. Line width or critical dimension measurements, largely the domain of scanning electron microscopy today, are shifting to optical scatterometry requiring neither vacuum nor electron beams. Recent optical techniques to determine junction depth and sheet resistance of ultra-shallow junctions, are examples where sophisticated contactless measurements coupled with computer analyses have proven to be very powerful. A very effective optical/electrical failure analysis technique is optical beam-induced resistance change. Charge-based methods made their appearance only a few years ago and have made a significant impact in the characterization of various material/device parameters. As shown on the first page, many other semiconductor material/device parameters are determined with contactless techniques and based on the progress during the past few years, we should expect continued progress in the contactless characterization area.

**References**
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