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Semiconductor Measurement Technology:

Survey of Optical Characterization Methods for Materials, Processing, and Manufacturing in the Semiconductor Industry

W. M. Bullis, S. Perkowitz, and D. G. Seiler

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W. Murray Bullis

Materials and Metrology
Sunnyvale, CA 94087-4015

S. Perkowitz

Emory University
Atlanta, GA 30322-2430

D. G. Seiler

Semiconductor Electronics Division
Electronics and Electrical Engineering Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899-0001

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W. M. Bullis

Materials & Metrology, Sunnyvale, CA 94087-4015

S. Perkowitz

Department of Physics, Emory University, Atlanta, GA 30322-2430

D. G. Seiler

National Institute of Standards and Technology, Gaithersburg, MD 20899

A preliminary report on this survey was presented at the International Workshop on Semiconductor Characterization: Present Status and Future Needs, January 30 to February 2, 1995, in Gaithersburg, Maryland (Reference [1]).

ABSTRACT

Contactless, nondestructive optical methods are used to characterize many critical properties of materials, processes, and devices in the semiconductor industry. To determine the extent of use and the relative importance of various optical methods in the industry, the Semiconductor Electronics Division of the National Institute of Standards and Technology conducted a survey of this field. The survey also sought to identify both advantages and limitations of these techniques as well as future requirements for and anticipated use of optical characterization methods within the semiconductor industry. Data from 42 firms were analyzed to show the impact of the methods, what they measure, their range and precision, and their cost. A significant finding of the study is the need expressed by many industrial users for improved standards and test methods for optical characterization, especially in the area of film thickness and composition.

Key words: compound semiconductors; ellipsometry; infrared spectroscopy; interferometry; optical characterization; optical microscopy; photoluminescence; photoreflectance; Raman scattering; reflectometry; scatterometry; semiconductors; silicon

BACKGROUND OF SURVEY

Many different methods are used for the characterization of materials and devices in the semiconductor industry. Among these, optical methods offer significant advantages compared to other techniques because they do not require the application of electrical contacts or other special sample preparation [2][3]. Because of the remote nature of optical probes, test samples or product wafers can be examined in situ during device processing. The probe beam can be focused to a small spot and scanned, allowing different regions of a sample to be characterized and maps of various properties to be produced. A recent workshop on the manufacture of integrated circuits noted that in-situ or real-time metrology is critically needed for the next generation of devices [2]. It also called for the development of new optical techniques, such as means to analyze and image an entire wafer surface to determine spatially resolved etch rate and end-point determination.

In response to such statements of industrial need, and growing out of its involvement with optical characterization methods such as ellipsometry, infrared absorption, and others, the Semiconductor Electronics Division of the National Institute of Standards and Technology (NIST) undertook to survey the extent of industrial use and relative importance of optical characterization methods in the semiconductor industry.

A questionnaire was designed by consultation among semiconductor scientists working at NIST, in industry, and in academia, to determine the advantages, limitations, and utilization of nine optical characterization methods: ellipsometry, infrared spectroscopy, interferometry, optical microscopy (visible and infrared), photoluminescence, photoreflectance, Raman scattering, reflectometry, and scatterometry. These were chosen because of their known or assumed value in characterizing semiconductors for electronic and photonic devices. Combined, these methods measure most of the properties that are important for such devices. This questionnaire is reproduced in Appendix A. It was sent to about 75 key individuals in U.S. industrial concerns that manufacture materials for devices, the devices themselves, or equipment to characterize or process semiconductors. This initial questionnaire was returned by 23 respondents.

Later, a slightly expanded version of the questionnaire, identical to the initial questionnaire except for additions to two of the questions, was developed. The additions were designed to elicit additional information about where and how optical characterization methods are applied in the industry. This version was distributed to nearly 75 more individuals in the industry in order to supplement the initial survey. A copy of this expanded questionnaire is reproduced in Appendix B. Nineteen respondents returned the expanded version of the questionnaire.

This report presents an analysis of the data from all 42 responses. Most of the information reported is based on the portions of the two versions that were identical. Additional data from the expanded version of the questionnaire are used to supplement the basic information. To facilitate further investigation of optical characterization technology, a literature base consisting of useful general surveys, and applications to specific materials and characterization problems is provided as Appendix C.

INTRODUCTION TO OPTICAL CHARACTERIZATION

Optical characterization principles, methods, and applications to the field of microelectronics and semiconductors have recently been reviewed [3][4]. This section briefly describes nine of the most widely used optical techniques (ellipsometry, infrared spectroscopy, interferometry, modulation spectroscopy, optical microscopy, photoluminescence, Raman scattering, reflectometry, and scatterometry) to provide a background and framework for the reader in order to better understand the results of the optical characterization survey.

Ellipsometry

Ellipsometry is based on the polarization transformation that occurs when a beam of polarized light is reflected from (or transmitted through) an interface or film [5][6]. This technique widely used to measure the thicknesses and optical constants of films important to semiconductor technology, such as SiO_2 on Si. Thicknesses measured are typically in the range of several nanometers to several hundred nanometers. Surface cleanliness of semiconductor wafers during processing can also be determined. In spectroscopic ellipsometry, the ellipsometric data are obtained as a function of wavelength. Then appropriate modeling and fitting can yield the dielectric functions and thicknesses of the layers in complex semiconductor/oxide multilayer systems. The dielectric functions give a complete picture of composition throughout the entire layered structures.

Infrared Spectroscopy

Infrared (IR) radiation interacts with semiconductor lattices, carriers, and impurities, and absorption in a uniform semiconductor layer is proportional to the layer thickness [7]. Infrared spectroscopy can then be used to determine impurity type and concentration in semiconductor materials, film thickness, semiconductor alloy composition, carrier density, and scattering time. These measurements can be made for bulk, film, and microstructure systems. In one application in Si, the amount of interstitial oxygen, whose concentration is critical, is determined from IR absorption [8]; correct values provide gettering action, reducing the level of other impurities, and hence, producing material with low leakage currents.

Interferometry

Interferometers are used to measure distances from a reference surface [9]. This type of instrument can be used directly in geometrical measurements such as the profile of an object such as a wafer or the flatness of a wafer surface. On a microscale, interferometers are used in surface texture instruments that observe areas ranging from a few hundred micrometers on a side to several millimeters on a side. An interferometer is also an integral component of one type of infrared spectrophotometer, the Fourier Transform Infrared (FTIR) spectrometer [7].

Modulation Spectroscopy

Modulation spectroscopy is a sensitive technique that can determine fine details of interband transitions in semiconductors. In semiconductor superlattices and other microstructures, detailed knowledge of the complex interband transitions can be used to characterize quantum well widths, potential barrier heights and widths, electric fields, the amount of strain in strain layer systems, and doping densities.

The principle behind modulation spectroscopy is that a periodic physical perturbation applied to a sample elicits the derivative of the sample's optical response to that perturbation. The derivative feature amplifies weak features in the response function and suppresses large constant background levels. This gives modulation methods very high sensitivity to small spectral features that are invisible in conventional spectroscopy.

Examples are electroreflectance, where a periodic electric field is applied to a sample while its reflectance spectrum is measured; and photoreflectance, where optically injected carriers from a chopped laser beam modulate the "built-in" surface or internal electric fields, thus modulating the reflectance of the sample. Other forms of modulation spectroscopy have been reviewed by Aspnes [10].

Optical Microscopy

Traditional optical microscopy is useful for a large number of applications such as examining topological features larger than $\sim 1.0\ \mu m$, examining defects, or counting etch pits [11]. Several specialized forms of optical microscopy are highly valuable: Nomarski, scanning laser, and microspectrophotometry. In Nomarski microscopy, interference methods are used to increase the contrast between small differences in the surface level of a semiconductor wafer. Scanning microscopy in both the visible and infrared spectral ranges allows two-dimensional imaging of features in a layer or structure. Finally, microspectrophotometry allows film thickness determination from spectral analysis of reflected light.

Scanning microscopy is also used in both the visible and the infrared spectral ranges to form two-dimensional images of inhomogeneities in a semiconductor. The form called confocal microscopy produces three-dimensional images. One visible light-scanning technique of special interest is the optical-beam-induced current method (abbreviated OBIC, or sometimes LBIC, for laser-beam-induced current), which detects grain boundaries, dislocations, and other defects in semiconductors and semiconductor devices. OBIC images represent spatial distributions of electrically active defects that include inclusions, strain, damage, precipitates, stacking faults, twin boundaries, dislocation clusters, and bandgap and doping variations.

Near-field scanning optical microscopy (NSOM) has recently been shown to be able to optically resolve features smaller than the diffraction limit. NSOM exploits the optical interaction arising from a sharp probe (optical fiber that terminates by tapering into a fine truncated cone) in close proximity to a sample in order to image the surface. This sharp probe is freely positioned or raster scanned across the surfaces, allowing highly localized exposures of the sample or generation of high-resolution images. Future work will determine the usefulness of NSOM in microelectronics manufacturing and its niche among competing technologies.

Photoluminescence

Photoluminescence (PL) depends on the fact that electrons residing in the valence band of a semiconductor can be excited via optical absorption to the conduction band, to an impurity, or to a defect level in the energy gap. PL results from radiative relaxation of an optically excited population, in which an excited electron usually returns to its initial state after a short time. If the excited electron returns to its initial state by radiative means, the process emits a photon whose energy is the difference between the excited and the initial state energies. The spectral distribution of the emitted photons shows an emission peak at the energy (or wavelength) corresponding to each excited level [12].

Photoluminescence can be used to determine the energy gap of a semiconductor sample. This technique is especially useful for III-V and II-VI ternary alloys like $Al_xGa_{1-x}As$ and $Zn_xCd_{1-x}Te$, because the energy gap, which varies with the compositional parameter x, must be accurately known for most applications. When this process is inverted, x can be found from the gap value and the known relation between gap energy and composition. Photoluminescence also detects the presence of impurities and crystalline defects in semiconductors that affect materials quality and device performance. Each impurity produces a characteristic feature or set of features in the spectrum. Hence, the impurity type can be identified, and multiple impurities can be detected in a single PL spectrum. In some cases, PL can measure the concentration of impurities. Comparison of PL peak halfwidths from sample to sample gives an indication of impurity concentration, carrier concentration, and crystal perfection. It is often necessary to cool the sample below room temperature to observe the best PL spectra. Cooling reduces the thermal broadening of the excited carrier spectrum of the order k_BT, and also reduces the importance of nonradiative de-excitation processes.

Raman Scattering

Raman scattering results when photons interact with optical lattice vibrations (phonons) of a semiconductor crystal lattice. It is a two-photon process, and is thus more complex than one-photon optical processes such as photoluminescence. If light impinges on the surface of a semiconductor, a large portion is reflected, transmitted, absorbed, or elastically scattered (Rayleigh scattering), with no change in frequency. A small part of the light interacts inelastically with phonon modes, so that the outgoing photons have frequencies shifted from the incoming values. These are the Raman-scattered photons. Since the photons can either gain energy or lose energy in their phonon interactions, the scattered light can be of higher frequency (anti-Stokes-shifted) or of lower frequency (Stokes-shifted) than the incident light. Because of statistical considerations, the Stokes modes are stronger and are usually the ones observed in Raman measurements at room temperature [13].

The way in which these phonons appear in a Raman spectrum depends on the crystallinity of a sample and on its crystal orientation. Hence, Raman scattering can determine whether a sample is amorphous or crystalline, and whether the crystal is of good quality or is altered by damage or imperfections. The method is also sensitive to strain effects, which change semiconductor lattice structure and hence, phonon frequencies. Since phonon frequencies and amplitudes in an alloy semiconductor like $Al_xGa_{1-x}As$ change with the degree of alloying, Raman scattering can be used to measure composition as well. By changing the wavelength of the light exciting the scattering, the penetration depth can be changed, which gives the capability to probe layered or inhomogeneous structures.

In microprobe Raman scattering, a microscope is coupled to the Raman system, making it possible to probe regions as small as ~ 1 μm across. This allows for the identification of contaminating impurities in extremely small regions of the specimen. In resonance Raman scattering, the scattering process is strengthened when the incoming photon energy matches the energy gap or other higher-order critical point energies in the sample's band structure. This resonance strengthens the inherently weak Raman process and also gives band structure information as well as phonon information.

Raman scattering has also been used to measure the temperature of semiconductor samples.

Reflectometry

Reflectometry is the workhorse technique for routine measurements of film thickness in the manufacture of silicon devices and circuits. It is based on the interference phenomena associated with reflection of a light beam from optical interfaces between two materials with different dielectric constants. Although not generally as powerful a technique as ellipsometry, refinements in optical models allow the rapid determination of layer thicknesses in single and multiple film stacks.

Scatterometry

Scatterometry is based on the measurement of the amount of light scattered from a surface. From this measurement, surface defects, surface topography, and subsurface defects can be evaluated [14]. Both integrating and angle-resolved scatterometers are employed. Integrating scatterometers have been used for more than a decade and a half for rapid and routine location of particulate contamination and other surface defects as well as for quantitatively determining the background scatter or "haze." More recently, andle-resolved scatterometry, long used in the optics industry for charactering very smooth surfaces, has begun to be applied to analysis of the surface texture of polished semiconductor surfaces.

DISTRIBUTION OF SURVEY RESPONSES

The number of survey responses and their distribution among types of firms represent a broad, but not completely representative, view of the semiconductor industry. Of the 42 responses, 17 came from materials suppliers, 13 from device manufacturers, and 12 from equipment suppliers, primarily makers of characterization equipment rather than processing equipment. Both small and large enterprises were represented. Different stages in the research-to-product cycle were also represented, as was determined by a question in the expanded version of the questionnaire that asked where in the cycle the optical methods are used. The results appear in Table I. The heaviest use comes in the areas of research and development and of process development so the survey overwhelmingly represents the pre-production portions of the cycle. Although some usage was reported for off-line diagnostics, quality control, and process control, the results are biased so that neither the requirements for nor the extent of the use of these techniques in materials and device production environments are fully indicated.

It should also be noted that the data reported here represent a mixture of responses from users of various materials. Thirteen of the responses came from users in the silicon industry, 11 from the III-V compound semiconductor area, six from the II-VI compound semiconductor area, and one from the flat-panel display area. Three of the responses did not provide information regarding the nature of materials characterized. Since test equipment can generally

Table I. Reported Usage of Optical Characterization Methods in Five Steps of the Research-to-Product Cycle

Optical Method	Research & Development	Process Development	Off-Line Diagnostics	Quality Control	Process Control
Ellipsometry	11	11	6	6	10
Infrared Spectroscopy	7	8	4	4	5
Interferometry	4	2	1	2	3
Optical Microscopy	9	5	5	5	6
Photoluminescence[a]	--	--	--	--	--
Photoreflectance	2	1	1	1	1
Raman Scattering	1		2		
Reflectometry	7	5	4	2	4
Scatterometry	4	4	2	2	2
Total Responses	45	36	25	22	31
Percent of Total	28	23	16	14	19

[a] No entries in this portion of the survey.

Table II. Use and Value of Optical Characterization Methods

Optical Method	Critical	Useful	Not Used	Percent Use	Value Rating	Final Rank
Optical microscopy	23	13	1	97	1.6	1
Ellipsometry	19	11	7	81	1.3	2
Infrared spectroscopy	20	8	7	80	1.4	2
Photoluminescence	10	9	14	58	0.9	3
Interferometry	9	7	14	53	0.8	4
Reflectometry	10	7	15	53	0.8	4
Scatterometry	8	9	15	53	0.8	4
Photoreflectance	4	11	17	47	0.6	5
Raman scattering	2	10	21	36	0.4	6
Total	105	85	111			
Other Methods*						
Photoconductive, photovoltaic	5	4				
Miscellaneous†	17	12				

* Added by respondents.

† All other methods combined. Each method was cited by only one respondent as either "critical" or "useful."

NOTE — The entries in the table represent a composite of usage on both silicon and compound semiconductor materials and devices.

be applied to any of these areas, responses from the equipment manufacturers were not included in the tally by material type.

The data reported here have not been analyzed as to which area the response originates. Because the silicon and compound semiconductor fields differ significantly in terms of the materials properties that must be controlled as well as in the mix between R&D and production activity, this lack of differentiation may cause a further bias of the reported results. Nevertheless, the results of the survey provide considerable insight into the requirements for and usage of optical characterization methods in the semiconductor industry. This insight provides useful guidance for the definition and prioritization of metrology development and standardization programs.

USE AND VALUE OF THE METHODS

Table II summarizes the responses relating to the industrial use and value of various optical characterization methods. Respondents were asked to rank each method as "critical" (essential for the end application), "useful" (the method gives valuable but not essential information), or "not used." In the table, the methods are listed in order of the extent of use, measured by the percentage of responses given as either critical or useful. The "value rating" is determined by weighting the number of "critical" responses by 2, the number of "useful" responses by 1, and the number of "not used" responses by 0, and dividing the weighted sum by the total number of responses. The last column is the ranking of the impact of the techniques based upon a combination of their value ratings and their percent use.

The method most widely used by respondents to the survey is optical microscopy and the method reported to be least used is Raman scattering. Although scatterometry falls well down on the list, it should be noted that this technique is the basis of scanning surface inspection systems (laser surface scanners) which are universally used by silicon materials and device manufacturers for automated particle counting. It should also be noted that reflectometry has been widely utilized for a considerable time in silicon device production to measure the thickness of thin films. More recently, ellipsometry is being explored as an in-situ method for controlling depositions of thin films on silicon, but in-situ metrology is still not widely employed in the industry.

In addition to the nine methods explicitly covered by the questionnaires, respondents were asked to indicate any other optical techniques that they considered to be either critical or useful. Nine respondents listed photovoltaic and photoconductive methods as either critical or useful. Taken together, these methods appear to be less widely used than Raman scattering. Twenty-nine other optical characterization methods were listed as critical or useful by one of the respondents.

PROPERTIES CHARACTERIZED

To determine what material properties are characterized by optical methods, 13 properties were explicitly listed in the survey. These properties were selected as those essential to characterize, design, and fabricate electronic and photonic devices. Table III summarizes the materials properties reported to be measured optically by the respondents to the survey. This table combines responses from both the silicon and compound semiconductor fields and from all sectors of the research-to-product cycle.

Bold-face entries represent a significant intersection of methods and properties. For instance, the responses to the survey show that ellipsometry is the most widely used method for determining film properties, but infrared spectroscopy, interferometry, and reflectometry are also utilized with some frequency. As discussed above, this result may arise from the biasing of the responses toward the product development portion of the research-to-product cycle, since it is well known that reflectometry is most widely used for this measurement in the production environment.

The last row of the table gives the number of listed materials properties reported to be measured by each technique. Many optical methods are reported to be extremely versatile; ellipsometry, infrared spectroscopy, photoluminescence, and Raman scattering are reported to be used for the measurement of 10 to 12 of the 13 listed material properties.

MEASURED MATERIALS AND DEVICES

Respondents to the questionnaire reported that they examine materials by optical methods about three times as often as they do devices, including both devices in process and finished devices. Table IV summarizes the relative usage of the listed optical characterization methods for materials and device characterization. The method most widely used for characterizing devices is microscopy, but even this technique was reported to be used more frequently for materials characterization. All of the other listed methods were reported to be overwhelmingly used for characterizing materials.

The table also indicates the type of material structures that were reported to be characterized by optical methods. Respondents to the survey measure materials most often in film form, with measurements on bulk materials a distant second. This no doubt reflects the fact that ellipsometry and reflectometry are the two primary techniques for measuring film thickness. Measurement of material microstructure (abbreviated "Micro" in the table) are most often made on relatively exotic III-V and II-VI ternary and quaternary material systems for photonic devices. Measurement of surfaces and interfaces appear to be made less frequently.

Table III. Material Properties Measured by Optical Methods, Listed Alphabetically by Technique

Material Property	Optical Method*								
	Ellipsometry	Infrared Spectroscopy	Interfer-ometry	Microscopy	Photolu-minescence	Photo-reflectance	Raman Scattering	Reflectometry	Scatter-ometry
Alloy Composition	6	**6**			**12**	**6**	**5**	3	
Carrier Density	3	1			3	3	2		
Carrier Mobility		1					2		
Carrier Lifetime	1	1			3				
Crystal Orientation	1	2					2		
Crystallinity	2	2		5	4	3	**6**	2	
Defect Density	1		2	**23**	3	1	1	1	**8**
Defect Type	1	1	1	**21**	3		2		1
Energy Band Gap	4	**5**	1		**14**	**5**		1	
Film Thickness	**29**	7	4	1	1			**10**	
Impurity Density	2	**8**		1	4	2	2		2
Impurity Type		**9**		1	**9**		2	1	1
Resistivity		2					1		
Total	50	45	8	52	56	20	25	18	12
Properties Measured	10	12	4	6	10	6	10	6	4

NOTE — The entries in the table represent a composite of usage on both silicon and compound semiconductor materials and devices.

Table IV. Relative Usage of Optical Characterization Methods on Materials and Devices

Optical Method	Materials Use	Material Configuration				Device Use
		Bulk	Film	Micro	Surface	
Ellipsometry	26	8	29	8	10	9
Infrared Spectroscopy	25	12	20	6	1	4
Interferometry	12	4	11	1	3	4
Optical Microscopy	26	12	27	12	13	17
Photoluminescence	19	11	16	11	5	4
Photoreflectance	11	3	7	6	6	3
Raman Scattering	8	4	7	4	2	2
Reflectometry	12	3	7	4	5	5
Scatterometry	11	9	8	4		3
Other	31	28	17	8	3	8
Total	181	94	149	64	48	59

Table V indicates that the respondents to the survey use optical characterization methods most often to measure silicon, closely followed by dielectrics and dielectric films, and Group III-V semiconductors. Group II-VI semiconductors and metals are cited much less frequently by the respondents to the survey. The citations for measurements on compound semiconductors also include ternary and quaternary compounds for photonic devices. This distribution tends to reflect the composition of the respondents to the survey as indicated in Table I as does the fact that more work was not reported on diamond and no work was reported on either silicon carbide or germanium-silicon alloys.

Table VI lists the electronic and photonic devices that were reported to be examined by optical characterization methods for both electronic and photonic devices. As might be expected from relative market sizes, photonic devices are characterized much less frequently than electronic devices.

Table V. Materials Reported to be Characterized by Optical Methods

Material	Number of Citations	Category Totals
SILICON		65
Crystalline and polycrystalline Si	57	
Amorphous Si	8	
DIELECTRICS, DIELECTRIC FILMS		60
Unspecified	12	
SiO_2, SiO_2/Si, SIMOX	29	
SiN_x	19	
GROUP III-V SEMICONDUCTORS		59
Unspecified	4	
GaAs	11	
AlGaAs, GaAs/AlGaAs systems	18	
InGaAs/GaAs/AlGaAs systems	11	
InGaAlP	7	
InSb, InAlSb, GaSb	6	
AlN	2	
GROUP II-VI SEMICONDUCTORS		36
Unspecified	5	
CdTe	6	
CdTe/CdZnTe systems	5	
HgCdTe, CdTe/HgCdTe systems	18	
ZnS	2	
METALS		15
Metal films, metals (unspecified)	8	
Aluminum	2	
Tin	1	
Titanium, titanium nitride	3	
Tungsten	1	
OTHER GROUP IV SEMICONDUCTORS		1
Diamond	1	
OTHER*		13

* Composites, contaminants, fluids, glass, high-T_c superconductors, photoresist.

Table VI. Applications of Optical Characterization Techniques to Electronic and Photonic Devices

Electronic Devices	Number of Citations	Photonic Devices	Number of Citations
Unspecified	15	Sources	
Microprocessors, memory	11	Quantum-well lasers	10
Silicon linear and digital ICs	10	Electroluminescent devices	4
HEMT, p-HEMT	9	Light emitting diodes	1
CMOS, MOS capacitor	5	Detectors, Solar Cells	
MESFET	4	Infrared, x-ray, unspecified	9
Magnetoresistors	2	Solar cells	1
		Other	
		Optical modulators	4
		Flat panel displays	1
Total	56	Total	30

RANGE AND PRECISION

Table VII summarizes the range, precision, and spatial characteristics of the reported optical measurement techniques. Empty boxes represent responses too limited, too scattered, or too ill-defined to tabulate. It proved difficult for the respondents to define all the details of quantitative measurement in brief form, and that may be one reason why the number of responses to the questions on these issues was not large. For some material properties, such as carrier lifetime, the range of measured values is enormous. Such large ranges suggest the diversity and flexibility of optical characterization methodology, but make it difficult to define a single overall value for precision. In addition, the concept of measurement precision does not apply to properties such as impurity type or defect type (for which the precision is indicated as not applicable, listed as "NA" in the table). Where a precision is given, it is the mean of the reported values, rounded to single-digit resolution. A precision value is quoted only where the database was relatively large and where the concept of precision appeared to be similarly defined by different users. Despite these limitations, the reported values provide a rough estimate of what optical methods can achieve.

Because optical characterization methods can be applied to a variety of sample sizes and shapes, respondents were asked to specify the sample size they examined. In most cases, the maximum area examined, listed in the third column of the table, was an entire 100 mm diameter

Table VII. Range and Precision of Measurements, and Maximum Sample Area Examined

Material Property	Number of Citations	Range	Mean Precision	Maximum Area, cm^2	Reset
Alloy Composition	11	0 to 100%	0.02	81	
Carrier Density	3	10^{17} to 10^{19} cm^{-3}	50%		
Carrier Mobility	1				
Carrier Lifetime	7	1 ps to 10 s	10%	Full wafer	
Crystal Orientation	2			Full wafer	
Crystallinity	4			176	
Defect Density	16	10^{1} to 10^{11} cm^{-2}		314	100 μm
Defect Type	6		NA	81	1 μm
Energy Band Gap	9	0 to 2 eV	0.03 eV	81	
Film Thickness	24	2 nm to 50 μm	2%	625	30 μm
Impurity Density	9			176	2 mm
Impurity Type	8		NA		
Resistivity	2				

wafer or larger. This is not meant to imply that the beam covers this entire area; in many cases the measured property is determined at many locations on the wafer surface to provide a map of the distribution of the property value. This is particularly important in assessing the uniformity of a crystal or of a deposited film.

The values in the last column of the table, labeled "Reset," relate to the reproducibility of spatial positioning of the optical beam on a sample. These data are subject to even greater limitations than the other table entries because they draw only on the responses to the expanded version of the questionnaire. These entries should be taken as only as order-of-magnitude estimates.

Whatever the absolute values of precision and the other attributes, it is essential that they serve the needs of the industry. To address this issue, survey respondents were asked to answer "Yes" or "No" to the following questions: Is the measurement precision adequate to your needs? Is the spatial resolution adequate? Is the accuracy of resetting to a given position on the sample adequate? Are standards or test methods needed to conduct the measurement? Are such standards or test methods available?

The responses are summarized in Table VIII. The first three columns of the table show that on average, the precision, resolution, and ability to reset are thought to be adequate about

Table VIII. Degree of Respondents' Satisfaction with Selected Attributes of Optical Methods for Characterizing Various Material Properties

Material Property	Precision Adequate?		Spatial Resolution Adequate?		Reset Capability Adequate?		Standards Needed?		Standards Available?	
	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
Alloy Composition	10	1	10	1			7	3	3	3
Carrier Density	1	2	1	1			2			2
Carrier Mobility	1		1							1
Carrier Lifetime	7		4	1	1	1	2	1	1	4
Crystal Orientation	1	1	1	1			2		2	1
Crystallinity	2	2	2	1	1		3		1	2
Defect Density	10	6	13	6	5	2	10	3	3	8
Defect Type	3	3	2	3	3	1	5	1		5
Energy Band Gap	9		7	1			4	3	2	2
Film Thickness	19	5	11	9	7	2	15	3	6	12
Impurity Density	3	6	6	1	1	2	5		2	4
Impurity Type	2	6	1	5	2		6	1		7
Resistivity	1	1	1	1	1		2			2
Total	69	33	60	31	21	8	63	15	20	53
Percent	68	32	66	34	72	28	81	19	27	73

Table IX. Degree of Use and Satisfaction with Other Attributes of Optical Characterization Techniques

Material Property	Sensitivity Adequate?		Automatic Loading				Data Communications				Speed Adequate?		Pattern Recognition			
			Used?		Adequate?		Used?		Adequate?				Used?		Adequate?	
	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
Carrier Lifetime	1		0	2		1	1	1	1	1	0	2			0	1
Defect Density	3	2	6	1	5	1	5	2	3	3	2	2	2	3	2	2
Defect Type	1	1	2	1	2	1	3	0	2	1	1	2	1	2	1	1
Film Thickness	6	2	7	2	5	2	7	3	4	3	4	3	3	4	1	2
Impurity Density	1	2	1	2	1	1	3	1	2	1	2	1	0	1	0	1
Impurity Type	1		1	0	1	0	1		1	0	1	0				
Resistivity			1	0	1	0	0	1	0	1	1	2	1	3	1	2
Total	13	7	18	8	15	6	20	8	13	10	11	12	7	13	5	9
Percent	65	35	69	31	71	29	71	29	56	44	48	52	35	65	36	64

70% of the time. However, there are wide variations in the responses for individual parameters. For instance, there is a high degree of satisfaction in the measurement of alloy composition, but concern about determination of impurity type. Regardless of the degree of satisfaction, the next column shows strong agreement with the proposition that standards and test methods are needed. By contrast, the last column shows nearly equally strong agreement that these are not now available. This expressed need for optical measurement standards is one of the important findings of the survey, clearly pointing to an area where NIST can contribute.

The expanded version of the survey requested further information about the measurement process. Table IX summarizes the responses to questions regarding the adequacy of the lower detection limit of measurement (measurement sensitivity), use and adequacy of automatic cassette loading of the measurement instrument (auto transport), use and adequacy of the ability to capture data and print it or send it to a host computer or storage medium (data communications), adequacy of the speed of the measurement system (speed), and use and adequacy of pattern recognition techniques (pattern recognition). The data in the table are from the responses to the expanded version of the questionnaire, and so there were a relatively small number of responses. Omitted parameters had no responses.

Two-thirds of the respondents were satisfied with the sensitivity of the measurement methods. Large fractions of the respondents use, and are satisfied with, automatic cassette loading of samples. Many capture the characterization data for further analysis by computer, but nearly half find this aspect unsatisfactory. More than half the users consider the speed of measurement to be inadequate. About one-third of the respondents use pattern recognition techniques, and two-thirds find these unsatisfactory. Although these data represent a very small sampling, they provide some indication of the degree of satisfaction and usage of these attributes of optical characterization techniques.

COMPARISON TO OTHER METHODS

Respondents were asked to identify reasons why they would prefer to utilize optical characterization techniques in preference to some other type of measurement method for a particular material property. Table X summarizes the responses to this question for a variety of material properties.

Entries in the second column of the table indicate the number of times that respondents stated that other nonoptical methods could be used to determine the same information. Each of the other columns represent a reason why the optical rather than the nonoptical method is used: higher speed or greater throughput of the optical method (speed), higher accuracy attainable with the optical method (acc), the nondestructive nature of the optical measurement (NDE), the reduced preparation effort required to make the optical measurement (prep), higher spatial

Table X. Reasons for Selection of Optical Methods over Other (Non-Optical) Techniques to Measure a Given Material Property

Material Property	Non-Optical Method Available	Speed	Acc	NDE	Prep	Res	Cost	Area
Alloy Composition	15	10	3	10	6	2	4	7
Carrier Density	5	4		2	1	1		2
Carrier Mobility	4	1		2	1	1		2
Carrier Lifetime	4	3	1	4	2	1		2
Crystal Orientation	3			1				1
Crystallinity	10	6	2	5	2		3	4
Defect Density	15	12	2	10	7	1	4	5
Defect Type	11	8		6	4	1	3	1
Energy Band Gap	7	6	4	6	3	2	2	4
Film Thickness	25	16	7	22	16	4	4	8
Impurity Density	12	7	1	10	7	2	4	4
Impurity Type	14	9	2	9	7	2	3	4
Resistivity	2			1	1			1
Total	127	82	22	88	57	17	27	45

Table XI. Reasons That Optical Characterization Methods Are Not Used

Method	Cost	Equipment	Support	Sensitivity	Precision	Standards	Other
Ellipsometry	4	2	3		1		1
Infrared Spectroscopy							1
Interferometry	1		2				2
Optical Microscopy				1	1	1	
Photoluminescence	1	2	3			1	1
Photoreflectance	1	1	1				2
Raman Scattering	5	1	5			2	3
Reflectometry	2	3	3				4
Scatterometry	1	1	4				3
Total	15	10	21	1	2	4	17

Table XII. Source of Optical Characterization Equipment Used in the Semiconductor Industry

Optical Characterization Method	Commercial Equipment	Equipment Built In-House
Ellipsometry	23	4
Infrared Spectroscopy	24	1
Interferometry	10	3
Optical Microscopy	31	2
Photoluminescence	7	9
Photoreflectance	5	5
Raman Scattering	4	5
Reflectometry	10	2
Scatterometry	9	4
Other	15	12
Total	138	47
Percent of Total	75	25

Table XIII. Costs Associated with the Use of Optical Characterization Equipment in the Semiconductor Industry

Optical Characterization Method	Cost ($1,000)	Operation ($1,000/year)	Staff (FTE)
Ellipsometry	97 (9 to 375)	4 (0 to 20)	0.5 (0 to 1.5)
Infrared spectroscopy	94 (20 to 300)	15 (0.5 to 85)	0.6 (0.1 to 2)
Interferometry	82 (2 to 300)	4 (0 to 16)	0.6 (0.1 to 1)
Optical microscopy	70 (3 to 1,000)	7 (0 to 80)	0.9 (0 to 10)
Photoluminescence	52 (15 to 150)	7 (0 to 20)	0.5 (0.2 to 1)
Photoreflectance	43 (10 to 150)	3 (0 to 10)	0.5 (0.1 to 1)
Raman scattering	96 (30 to 150)	8 (0 to 20)	0.5 (0.2 to 1)
Reflectometry	75 (10 to 320)	2 (0 to 10)	0.6 (0.1 to 2)
Scatterometry	117 (25 to 350)	5 (0 to 35)	0.7 (0.1 to 2)
Other	87 (8 to 250)	11 (0 to 80)	0.8 (0.1 to 2)

resolution of the optical method (res), the lower cost of the optical method (cost), and the capability of the optical method to measure over an extended area (area). The nondestructive nature and high speed of optical techniques were cited as the most important reasons for preferring these methods over others. Reasons cited less frequently included the reduced preparation effort required and the ability to examine different portions of a sample.

Respondents were also asked to indicate reasons why they do not employ optical techniques that they would expect to find useful for characterizing materials or devices. Table XI summarizes the small number of responses to this question. Lack of technical support, presumably either by the instrument manufacturer or from an in-house support group, was cited most frequently as the reason that potentially useful optical methods are not employed. Cost and lack of commercial equipment were listed as the next most important considerations. The importance of the availability of commercial equipment was indicated by the fact that three out of four applications reported by survey respondents utilized commercially available equipment, as shown in Table XII.

The capital, operational, and staff investments necessary to carry out optical characterization as reported by the respondents to the survey are summarized in Table XIII. Equipment costs vary greatly, in some cases by a factor of more than 10. This may reflect the presence of multiple measurement stations, in-house *vs.* commercial costs, and the degree of automation. For example, as noted previously, three out of four applications involve the use of commercially available apparatus, although in the several areas where there is a significant usage of in-house equipment, the reported equipment costs tended to be somewhat lower.

COST ISSUES

Operational costs also vary widely, probably for similar reasons, and because different organizations may allocate such costs differently. Some of the diversity in the staff numbers may also reflect how staff time is allocated for internal budgeting, as well as the number of stations. Despite the wide variation in both equipment and operating costs reported by the respondents to the survey, cost is perceived as a major inhibiting factor to the use of optical characterization methods by many in the industry.

COMMENTS FROM RESPONDENTS

In addition to responding to fixed questions, respondents were asked for their free-form comments in four areas: optical characterization methods not previously mentioned that the respondent would find useful for future applications, ways in which NIST could help to improve optical characterization methods, application of optical characterization techniques to non-semiconductor materials, and any other important issues not covered by the questions in the survey form. Comments on the first, second, and fourth of these issues were received from a very small fraction of the total number of respondents. Many respondents had identified in their responses to earlier questions in the survey that they measure nonsemiconductor materials associated with device structures, such as dielectric and metal films, with the use of optical characterization techniques.

Half a dozen respondents mentioned spectroscopic ellipsometry as well worth further development. Two would like to see development of photoluminescence, one suggesting a need for a packaged system that could operate over the temperature range from 10 K to 400 K. For both techniques, cost was mentioned as a barrier to future use.

The biggest issue raised concerning NIST involvement was related to developing reference materials for optical characterization. This was mentioned in nearly two-thirds of the responses made in essay form. Examples where such reference materials might be most useful include film thickness standards for SiO_2/Si and multilayer films 2 nm to 10 nm thick, standards for defects and surface microroughness in silicon, and standards for spectroscopic ellipsometry. Requests were also made for standardized measurement procedures and analytical software, a catalog of photoluminescent spectral signatures from impurities, and workshops.

Some respondents were concerned about the lack of fundamental work in the physics of characterization. Most instrument manufacturers were thought to be too small to carry out such research, and university work in this area was perceived as limited in scope. The database for optical characterization activities was seen as lacking, for instance in energy gap *vs.* alloy content for AlGaAs and InGaAs. Some respondents looked to NIST to establish such data. Two respondents consider in-situ measurement and optically-guided control of sample growth as important future possibilities not treated in the survey. One felt that despite the obvious advantages of optical characterization as a nondestructive technique, its benefits and drawbacks have yet to be clearly laid out to the industry.

SUMMARY

Optical methods are used to characterize a wide variety of material systems. The 42 responses from different types of firms show that these techniques are heavily used in industrial research and development activities. Of the specific techniques identified, microscopy has had the greatest impact, and Raman scattering, the least. The nondestructive nature of optical methods is a major reason both for their present use and for their future importance for in-situ characterization. Lack of technical support is the main reason given for not employing optical techniques.

The respondents' largest single application of optical techniques is to silicon, but optical characterization of dielectrics and dielectric films and Group III-V semiconductors is nearly as widespread. A diverse set of devices is examined by these techniques. Among the respondents to the survey, electronic devices are examined by optical characterization methods twice as often as photonic ones.

The range of values that can be measured for many properties is broad, and precision ranges from moderate to excellent. Precision, sensitivity, and spatial resolution are thought adequate for two out of every three current applications, but deficiencies were noted in some specific areas. Ellipsometry and infrared spectroscopy are reported to be the most expensive methods; photoluminescence and photoreflectance, the least expensive. Many users carry out optical characterization with a relatively modest investment, but the reported range of costs involved was very large.

The need for reference materials and standard test methods for optical techniques is an important finding of the survey. A number of respondents would find workshops on these techniques to be useful.

ACKNOWLEDGMENTS

The authors gratefully acknowledge E. Jane Walters of the Semiconductor Electronics Division whose expert assistance enabled this survey of the semiconductor industry to be successfully accomplished.

REFERENCES

[1] S. Perkowitz, D. G. Seiler, and W. M. Bullis, "Optical Characterization of Materials and Devices for the Semiconductor Industry: Trends and Needs," *Semiconductor Characterization: Present Status and Future Needs,* W. M. Bullis, D. G. Seiler, and A. C. Diebold, eds. (AIP Press, Woodbury, NY, 1995), pp. 422–427.

[2] *Proceedings of the International Workshop in Process Control Measurements for Advanced IC Manufacturing*, November 9–10, 1992, Austin, Texas, P. H. Langer and W. M. Bullis, eds. (Semiconductor Equipment and Materials International, Mountain View, California, 1993), pp. 5, 13.

[3] S. Perkowitz, D. G. Seiler, and W. M. Duncan, "Optical Characterization in Microelectronics Manufacturing," *J. Res. Natl. Inst. Stand. Technol.* **99** (5), 605–639 (1994).

[4] S. Perkowitz, *Optical Characterization of Semiconductors: Infrared, Raman, and Photoluminescence Spectroscopy* (Academic Press, London, 1993).

[5] H. G. Tompkins, *A User's Guide to Ellipsometry* (Academic Press, Inc., San Diego, 1993).

[6] R. M. A. Azzam and N. M. Bashara, *Ellipsometry and Polarized Light* (North Holland, New York, 1989).

[7] J. R. Ferraro and K. Krishnan, *Practical Fourier Transform Infrared Spectroscopy: Industrial and Laboratory Chemical Analysis* (Academic Press, San Diego, 1990).

[8] W. M. Bullis, "Oxygen Concentration Measurement," in *Oxygen in Silicon*, F. Shimura, ed. (Academic Press, Inc., Boston, 1994), Chapter 4.

[9] N. Bobroff, "Recent Advances in Displacement Measuring Interferometry," *Measurement Science and Technology* **4**, 907-926 (1993).

[10] D. E. Aspnes, "Modulation Spectroscopy/Electric Field Effects on the Dielectric Function of Semiconductors," *Handbook on Semiconductors*, Vol. 2, T. S. Moss and M. Balkanski, eds. (North Holland, New York, 1980), p. 109.

[11] See, for example, the section on Optical Microscopy in Reference [3], pp. 617-623.

[12] M. Tajima, "Quantitative Impurity Analysis in Si by the Photoluminescence Technique," in *Japan Annual Reviews in Electronics, Computers, and Telecommunications - Semiconductor Technology*, J. Nishizawa, ed. (OHM-North Holland, 1982).

[13] J. G. Grasselli and B. J. Bulkin, eds., *Analytical Raman Spectroscopy* (Wiley, New York, 1990).

[14] J. C. Stover, *Optical Scattering: Measurement and Analysis*, 2nd Edition (SPIE Optical Engineering Press, Bellingham, Washington, 1995).

Appendix A

Initial Survey Form

NIST form # (unnumbered)
OMB Approval # 0693-0014
Expiration Date: 06/30/93

Public reporting burden for this collection of information is estimated to average one hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Dr. David G. Seiler, Semiconductor Electronics Division, National Institute of Standards and Technology, Gaithersburg, MD 20899, and to the Office of Management and Budget, Paperwork Reduction Project (OMB # 0693-0014), Washington, DC 20503. NOTE: DO NOT SEND COMPLETED FORM TO OMB. USE ADDRESS SHOWN ON PAGE 8.

OPTICAL CHARACTERIZATION METHODS FOR MATERIALS, PROCESSING, AND MANUFACTURING IN THE SEMICONDUCTOR INDUSTRY

QUESTIONNAIRE FOR INDUSTRIAL USERS OF OPTICAL CHARACTERIZATION METHODS

(1) Check the appropriate column below to show whether you use any of the listed optical methods to characterize, diagnose, or help in processing either: (a) semiconductors or semiconductor substrates for electronic, photonic, or other devices; (b) the devices themselves. "Critical" means the optical method is essential for your end application; "useful" means the method gives valuable but not essential information.

	Critical	Useful	Don't use
Ellipsometry	____	____	______
Infrared spectroscopy (e.g., FTIR)	____	____	______
Interferometry	____	____	______
Optical microscopy (visible or infrared)	____	____	______
Photoluminescence	____	____	______
Photoreflectance	____	____	______
Raman scattering	____	____	______
Reflectometry	____	____	______
Scatterometry	____	____	______
Other methods (indicate)*	____	____	______
______________________	____	____	______
______________________	____	____	______
______________________	____	____	______
______________________	____	____	______
______________________	____	____	______

*Add any other techniques you use such as: time-resolved, synchrotron, free-electron laser, photothermal, photoacoustic, laser-beam-induced current, optical-beam-induced reflectance, nonlinear spectroscopy, attenuated total reflectance, reflectance-difference, photo-injection, photoconductive, photovoltaic.

(2) For each critical or useful method checked in Question 1, indicate below in the material/device column whether it is used on a material, or on a device. If the former, identify the material (for example, high-resistivity Si, or AlGaAs), and the end device which uses it. If a device, identify it (for example, light-emitting diode) and the material of which it is made. In all cases, check whether the material involved is in bulk, film, or microstructure form (any multiple layer structure such as a heterostructure, superlattice, or multiple quantum well), abbreviated "micro."

	Material or device?	Material	Bulk	Film	Micro	Surface/ Interface	Device
Ellipsometry							
Infrared spectroscopy							
Interferometry							
Optical microscopy							
Photoluminescence							
Photoreflectance							
Raman scattering							
Reflectometry							
Scatterometry							
Other*________							

*Identify

(3) For each critical or useful method you checked in Question 1, indicate below what material or device parameter it measures, by a check at the appropriate junction of method (listed horizontally) and parameter (listed vertically). The methods in Question 1 are abbreviated as ELL, ellipsometry; IR, infrared; IN, interferometry; MIC, microscopy; PL, photoluminescence; PR, photoreflectance; RAM, Raman; REF, reflectometry; SC, scatterometry; other.

METHODS

PARAMETERS	ELL	IR	IN	MIC	PL	PR	RAM	REF	SC	OTHER*	OTHER*
Alloy composition											
Carrier density											
Carrier mobility											
Carrier lifetime											
Crystal orientation											
Crystallinity											
Defect density											
Defect type											
Energy band gap											
Film thickness											
Impurity density											
Impurity type											
Resistivity											
Other*________											

*Identify

(4) For each parameter you checked in Question 3, give the range of values measured, and the precision or uncertainty achieved (if you do a statistical analysis, please use a single standard deviation) of the measurement as a ± percent of the quantity measured, and indicate if this is adequate (yes or no). If the parameter is measured over a spatial extent (example: to produce a map of defect density over a silicon wafer), in the "spatial" column, state the total size of the area you examined, the spatial resolution used, and whether this resolution is adequate. Also indicate if the measurement requires physical standards or test methods, and what types (such as wavelength, intensity, or thickness standards), and if adequate standards or test methods are available.

	Range	Precision	Adequate	Spatial	Adequate	Standards/ Test Methods	Adequate
Alloy composition	______	______	______	______	______	______	______
Carrier density	______	______	______	______	______	______	______
Carrier mobility	______	______	______	______	______	______	______
Carrier lifetime	______	______	______	______	______	______	______
Crystal orientation	______	______	______	______	______	______	______
Crystallinity	______	______	______	______	______	______	______
Defect density	______	______	______	______	______	______	______
Defect type	______	______	______	______	______	______	______
Energy band gap	______	______	______	______	______	______	______
Film thickness	______	______	______	______	______	______	______
Impurity density	______	______	______	______	______	______	______
Impurity type	______	______	______	______	______	______	______
Resistivity	______	______	______	______	______	______	______
Other*______	______	______	______	______	______	______	______
______	______	______	______	______	______	______	______
______	______	______	______	______	______	______	______
______	______	______	______	______	______	______	______

*Identify

If you have indicated that inadequacies exist for these measurements, please comment on their nature and significance and what is needed in Question 9 or 10. Including an estimate of the cost to your company arising from the inadequacies you have identified would be helpful.

(5) For each parameter you checked in Question 3, check the "yes" column below if the same information can be obtained by non-optical methods. For each "yes" answer, check the reason(s) why you chose the optical rather than the non-optical method, abbreviated as follows: SPD — higher speed or greater throughput; ACC — higher accuracy; NDE — nondestructive nature of optical measurement; PRE — reduced preparation effort; HSR — high spatial resolution needed; COS — lower cost; SPA — capability to measure over a spatial extent; other.

	YES	SPD	ACC	NDE	PRE	HSR	COS	SPA	OTHER*	OTHER*
Alloy composition	___	___	___	___	___	___	___	___	______	______
Carrier density	___	___	___	___	___	___	___	___	______	______
Carrier mobility	___	___	___	___	___	___	___	___	______	______
Carrier lifetime	___	___	___	___	___	___	___	___	______	______
Crystal orientation	___	___	___	___	___	___	___	___	______	______
Crystallinity	___	___	___	___	___	___	___	___	______	______
Defect density	___	___	___	___	___	___	___	___	______	______
Defect type	___	___	___	___	___	___	___	___	______	______
Energy band gap	___	___	___	___	___	___	___	___	______	______
Film thickness	___	___	___	___	___	___	___	___	______	______
Impurity density	___	___	___	___	___	___	___	___	______	______
Impurity type	___	___	___	___	___	___	___	___	______	______
Resistivity	___	___	___	___	___	___	___	___	______	______
Other*__________	___	___	___	___	___	___	___	___	______	______
______________	___	___	___	___	___	___	___	___	______	______
______________	___	___	___	___	___	___	___	___	______	______

*Identify

(6) For each critical or useful method in Question 1, check whether you use commercial equipment, or a facility designed or built in-house. Give the approximate cost to buy or build the equipment; yearly operating cost, including maintenance, and supplies such as cryogens; and the number of full-time equivalent (FTE) people needed to run the facility, obtain data, and interpret data.

	Equipment			Yearly	
	Commercial	In-house	Equipment cost	Operating cost	FTE people
Ellipsometry	______	______	______	______	______
Infrared	______	______	______	______	______
Interferometry	______	______	______	______	______
Optical microscopy	______	______	______	______	______
Photoluminescence	______	______	______	______	______
Photoreflectance	______	______	______	______	______
Raman scattering	______	______	______	______	______
Reflectometry	______	______	______	______	______
Scatterometry	______	______	______	______	______
Other*______________	______	______	______	______	______
______________	______	______	______	______	______

*Identify

(7) Consider any methods in Question 1 which you do not currently use, but which could be helpful. For each, check the reason(s) you do not use it: cost of installing and/or operating; lack of commercial equipment; lack of technical support for the equipment or the data analysis; inadequate sensitivity; inadequate precision; inadequate physical standards or test methods; other.

	Cost	Lack of commercial equipment	Lack of technical support	Inadequate sensitivity	Inadequate precision	Inadequate Standards/ Test Methods	Other*
Ellipsometry	___	______	______	______	______	______	______
Infrared	___	______	______	______	______	______	______
Interferometry	___	______	______	______	______	______	______
Optical microscopy	___	______	______	______	______	______	______
Photoluminescence	___	______	______	______	______	______	______
Photoreflectance	___	______	______	______	______	______	______
Raman scattering	___	______	______	______	______	______	______
Reflectometry	___	______	______	______	______	______	______
Scatterometry	___	______	______	______	______	______	______
Other*__________	___	______	______	______	______	______	______
__________	___	______	______	______	______	______	______

* Identify

(8) Please list and briefly describe any optical methods you have not yet mentioned which might develop value for meeting your future characterization needs.

(9) Please add any comments you wish to make about the use of optical characterization for your applications. Identification of what you consider to be the important issues, especially any not addressed by this questionnaire, is welcome.

(10) In what specific ways could NIST help you to improve your optical characterization methods?

(11) What non-semiconductor materials are also characterized by optical methods in your work? Please list the materials and the optical method used.

____

____

____

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Please return this Questionnaire to the following address:

Dr. David G. Seiler
National Institute of Standards and Technology
Semiconductor Electronics Division
Bldg. 225, Room A305
Gaithersburg, MD 20899

Telephone: 301-975-2074
FAX: 301-948-4081

If you would like to receive a copy of the final report, please write your name and address below. If you would be willing to receive a telephone call regarding questions about your response, please include your telephone number. Providing this information in no way will compromise our promise of confidentiality.

Name ____

____

____

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Telephone ____

Appendix B

Expanded Survey Form

NIST form # (unnumbered)
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OPTICAL CHARACTERIZATION METHODS FOR MATERIALS, PROCESSING, AND MANUFACTURING IN THE SEMICONDUCTOR INDUSTRY

QUESTIONNAIRE FOR INDUSTRIAL USERS OF OPTICAL CHARACTERIZATION METHODS

(1) Check the appropriate column below to show whether you use any of the listed optical characterization methods: (a) as a materials supplier of semiconductors or semiconductor substrates for electronic, photonic, or other devices; (b) as a manufacturer of the devices themselves; or (c) as an equipment supplier. In all cases, please insert the appropriate letters (a), (b), or (c) in the "Critical" and "Useful" columns. "Critical" means the optical method is essential for your end application; ''useful'' means the method gives valuable but not essential information.

	Type of Use							
	R&D	Process Devel.	Off-Line Diagnos.	Quality Control	Process Control	Critical	Useful	Don't use
Ellipsometry	___	___	___	___	___	___	___	___
Infrared spectroscopy (e.g., FTIR)	___	___	___	___	___	___	___	___
Interferometry	___	___	___	___	___	___	___	___
Optical microscopy (visible or infrared)	___	___	___	___	___	___	___	___
Photoluminescence	___	___	___	___	___	___	___	___
Photoreflectance	___	___	___	___	___	___	___	___
Raman scattering	___	___	___	___	___	___	___	___
Reflectometry	___	___	___	___	___	___	___	___
Scatterometry	___	___	___	___	___	___	___	___
Other methods (indicate)*	___	___	___	___	___	___	___	___
___________	___	___	___	___	___	___	___	___
___________	___	___	___	___	___	___	___	___
___________	___	___	___	___	___	___	___	___

*Add any other techniques you use such as: time-resolved, synchrotron, free-electron laser, photothermal, photoacoustic, laser-beam-induced current, optical-beam-induced reflectance, nonlinear spectroscopy, attenuated total reflectance, reflectance-difference, photo-injection, photoconductive, photovoltaic.

(2) For each critical or useful method checked in Question 1, indicate below in the material/device column whether it is used on a material, or on a device. If the former, identify the material (for example, high-resistivity Si, or AlGaAs), and the end device which uses it. If a device, identify it (for example, light-emitting diode) and the material of which it is made. In all cases, check whether the material involved is in bulk, film, or microstructure form (any multiple layer structure such as a heterostructure, superlattice, or multiple quantum well), abbreviated "micro."

	Material or device?	Material	Bulk	Surface/ Film	Micro	Interface	Device
Ellipsometry							
Infrared spectroscopy							
Interferometry							
Optical microscopy							
Photoluminescence							
Photoreflectance							
Raman scattering							
Reflectometry							
Scatterometry							
Other*____________							

*Identify

(3) For each critical or useful method you checked in Question 1, indicate below what material or device parameter it measures, by a check at the appropriate junction of method (listed horizontally) and parameter (listed vertically). The methods in Question 1 are abbreviated as ELL, ellipsometry; IR, infrared; IN, interferometry; MIC, microscopy; PL, photoluminescence; PR, photoreflectance; RAM, Raman; REF, reflectometry; SC, scatterometry; other.

METHODS

PARAMETERS	ELL	IR	IN	MIC	PL	PR	RAM	REF	SC	OTHER*	OTHER*
Alloy composition	___	__	__	___	__	___	___	___	__	______	______
Carrier density	___	__	__	___	__	___	___	___	__	______	______
Carrier mobility	___	__	__	___	__	___	___	___	__	______	______
Carrier lifetime	___	__	__	___	__	___	___	___	__	______	______
Crystal orientation	___	__	__	___	__	___	___	___	__	______	______
Crystallinity	___	__	__	___	__	___	___	___	__	______	______
Defect density	___	__	__	___	__	___	___	___	__	______	______
Defect type	___	__	__	___	__	___	___	___	__	______	______
Energy band gap	___	__	__	___	__	___	___	___	__	______	______
Film thickness	___	__	__	___	__	___	___	___	__	______	______
Impurity density	___	__	__	___	__	___	___	___	__	______	______
Impurity type	___	__	__	___	__	___	___	___	__	______	______
Resistivity	___	__	__	___	__	___	___	___	__	______	______
Other*__________	___	__	__	___	__	___	___	___	__	______	______
______________	___	__	__	___	__	___	___	___	__	______	______
______________	___	__	__	___	__	___	___	___	__	______	______
______________	___	__	__	___	__	___	___	___	__	______	______
______________	___	__	__	___	__	___	___	___	__	______	______

*Identify

(4a) For each parameter you checked in Question 3, give the range of values measured, and the precision or uncertainty achieved (if you do a statistical analysis, please use a single standard deviation) of the measurement as a ± percent of the quantity measured, and indicate if this is adequate (yes or no). If the parameter is measured over a spatial extent (example: to produce a map of defect density over a silicon wafer), in the ''spatial'' column, state the total size of the area you examined, the spatial resolution used, and whether this resolution is adequate. Also indicate if the measurement requires physical standards or test methods, and what types (such as wavelength, intensity, or thickness standards), and if adequate standards or test methods are available.

	Range	Precision	Adequate	Spatial Area	Spatial Resolution	Adequate	Standards/ Test Methods	Adequate
Alloy composition	____	______	____	___	________	____	______	____
Carrier density	____	______	____	___	________	____	______	____
Carrier mobility	____	______	____	___	________	____	______	____
Carrier lifetime	____	______	____	___	________	____	______	____
Crystal orientation	____	______	____	___	________	____	______	____
Crystallinity	____	______	____	___	________	____	______	____
Defect density	____	______	____	___	________	____	______	____
Defect type	____	______	____	___	________	____	______	____
Energy band gap	____	______	____	___	________	____	______	____
Film thickness	____	______	____	___	________	____	______	____
Impurity density	____	______	____	___	________	____	______	____
Impurity type	____	______	____	___	________	____	______	____
Resistivity	____	______	____	___	________	____	______	____
Other*								
____________	____	______	____	___	________	____	______	____
____________	____	______	____	___	________	____	______	____
____________	____	______	____	___	________	____	______	____

*Identify

If you have indicated that inadequacies exist for these measurements, please comment on their nature and significance and what is needed in Question 9 or 10. Including an estimate of the cost to your company arising from the inadequacies you have identified would be helpful.

(4b) For each parameter you checked in Question 3, please provide these further details. Sensitivity refers to the lower detection limit; auto transport, to the availability of automatic cassette loading of the instrument; communications, to the ability to capture data and either print it out or send it to a host computer or to storage media; positioning, to the ability to come back to the same location on the sample; pattern recognition, to the issue of finding a location within a pattern which contains a test element, defect, or other structure which can be examined by the measurement method.

	Measurement Speed		Sensitivity		Auto Transport		Communications		Positioning		Pattern Recognition	
	Value	Adequate	Value	Adequate	Used	Adequate	Used	Adequate	Value	Adequate	Used	Adequate
Alloy composition	____	____	____	____	____	____	____	____	____	____	____	____
Carrier density	____	____	____	____	____	____	____	____	____	____	____	____
Carrier mobility	____	____	____	____	____	____	____	____	____	____	____	____
Carrier lifetime	____	____	____	____	____	____	____	____	____	____	____	____
Crystal orientation	____	____	____	____	____	____	____	____	____	____	____	____
Crystallinity	____	____	____	____	____	____	____	____	____	____	____	____
Defect density	____	____	____	____	____	____	____	____	____	____	____	____
Defect type	____	____	____	____	____	____	____	____	____	____	____	____
Energy band gap	____	____	____	____	____	____	____	____	____	____	____	____
Film thickness	____	____	____	____	____	____	____	____	____	____	____	____
Impurity density	____	____	____	____	____	____	____	____	____	____	____	____
Impurity type	____	____	____	____	____	____	____	____	____	____	____	____
Resistivity	____	____	____	____	____	____	____	____	____	____	____	____
Other* ________	____	____	____	____	____	____	____	____	____	____	____	____
____________	____	____	____	____	____	____	____	____	____	____	____	____
____________	____	____	____	____	____	____	____	____	____	____	____	____
____________	____	____	____	____	____	____	____	____	____	____	____	____

*Identify

If you have indicated that inadequacies exist for these measurements, please comment on their nature and significance and what is needed in Question 9 or 10. Including an estimate of the cost to your company arising from the inadequacies you have identified would be helpful.

(5) For each parameter you checked in Question 3, check the "yes" column below if the same information can be obtained by non-optical methods. For each "yes" answer, check the reason(s) why you chose the optical rather than the non-optical method, abbreviated as follows: SPD — higher speed or greater throughput; ACC — higher accuracy; NDE — nondestructive nature of optical measurement; PRE — reduced preparation effort; HSR — high spatial resolution needed; COS — lower cost; SPA — capability to measure over a spatial extent; other.

	YES	SPD	ACC	NDE	PRE	HSR	COS	SPA	OTHER*	OTHER*
Alloy composition	___	___	___	___	___	___	___	___	______	______
Carrier density	___	___	___	___	___	___	___	___	______	______
Carrier mobility	___	___	___	___	___	___	___	___	______	______
Carrier lifetime	___	___	___	___	___	___	___	___	______	______
Crystal orientation	___	___	___	___	___	___	___	___	______	______
Crystallinity	___	___	___	___	___	___	___	___	______	______
Defect density	___	___	___	___	___	___	___	___	______	______
Defect type	___	___	___	___	___	___	___	___	______	______
Energy band gap	___	___	___	___	___	___	___	___	______	______
Film thickness	___	___	___	___	___	___	___	___	______	______
Impurity density	___	___	___	___	___	___	___	___	______	______
Impurity type	___	___	___	___	___	___	___	___	______	______
Resistivity	___	___	___	___	___	___	___	___	______	______
Other*__________	___	___	___	___	___	___	___	___	______	______
______________	___	___	___	___	___	___	___	___	______	______
______________	___	___	___	___	___	___	___	___	______	______

*Identify

(6) For each critical or useful method in Question 1, check whether you use commercial equipment, or a facility designed or built in-house. Give the approximate cost to buy or build the equipment; yearly operating cost, including maintenance, and supplies such as cryogens; and the number of full-time equivalent (FTE) people needed to run the facility, obtain data, and interpret data.

	Equipment		Equipment	Yearly	FTE
	Commercial	In-house	cost	Operating cost	people
Ellipsometry	____	____	____	____	____
Infrared	____	____	____	____	____
Interferometry	____	____	____	____	____
Optical microscopy	____	____	____	____	____
Photoluminescence	____	____	____	____	____
Photoreflectance	____	____	____	____	____
Raman scattering	____	____	____	____	____
Reflectometry	____	____	____	____	____
Scatterometry	____	____	____	____	____
Other*____________	____	____	____	____	____
____________	____	____	____	____	____

*Identify

(7) Consider any methods in Question 1 which you do not currently use, but which could be helpful. For each, check the reason(s) you do not use it: cost of installing and/or operating; lack of commercial equipment; lack of technical support for the equipment or the data analysis; inadequate sensitivity; inadequate precision; inadequate physical standards or test methods; other.

	Cost	Lack of commercial equipment	Lack of technical support	Inadequate sensitivity	Inadequate precision	Inadequate Standards/ Test Methods	Other*
Ellipsometry	____	____	____	____	____	____	____
Infrared	____	____	____	____	____	____	____
Interferometry	____	____	____	____	____	____	____
Optical microscopy	____	____	____	____	____	____	____
Photoluminescence	____	____	____	____	____	____	____
Photoreflectance	____	____	____	____	____	____	____
Raman scattering	____	____	____	____	____	____	____
Reflectometry	____	____	____	____	____	____	____
Scatterometry	____	____	____	____	____	____	____
Other*__________	____	____	____	____	____	____	____
__________	____	____	____	____	____	____	____

* Identify

(8) Please list and briefly describe any optical methods you have not yet mentioned which might develop value for meeting your future characterization needs.

(9) Please add any comments you wish to make about the use of optical characterization for your applications. Identification of what you consider to be the important issues, especially any not addressed by this questionnaire, is welcome.

(10) In what specific ways could NIST help you to improve your optical characterization methods?

(11) What non-semiconductor materials are also characterized by optical methods in your work? Please list the materials and the optical method used.

____

____

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Please return this Questionnaire to the following address:

Dr. David G. Seiler
National Institute of Standards and Technology
Semiconductor Electronics Division
Bldg. 225, Room A305
Gaithersburg, MD 20899

Telephone: 301-975-2074
FAX: 301-948-4081

If you would like to receive a copy of the final report, please write your name and address below. If you would be willing to receive a telephone call regarding questions about your response, please include your telephone number. Providing this information in no way will compromise our promise of confidentiality.

Name ____

____

____

____

Telephone ____

Appendix C

Bibliography

Book Length Reviews and Compendia

C. R. Brundle, C. A. Evans, and S. Wilson, eds., *Encyclopedia of Materials Characterization* (Butterworth-Heinemann, Boston, 1992).

W. M. Bullis, D. G. Seiler, and A. C. Diebold, eds., *Semiconductor Characterization: Present Status and Future Needs* (AIP Press, Woodbury, New York, 1995).

J. R. Ferraro and K. Krishnan, eds., *Practical Fourier Transform Infrared Spectroscopy* (Academic Press, San Diego, 1990).

J. G. Grasselli and B. J. Bulkin, eds., *Analytical Raman Spectroscopy* (Wiley, New York, 1990).

S. Perkowitz, *Optical Characterization of Semiconductors: Infrared, Raman, and Photoluminescence Spectroscopy* (Academic Press, London, 1993).

D. G. Seiler and C. L. Littler, eds., *The Spectroscopy of Semiconductors*, in Semiconductors and Semimetals (Academic Press, Inc., New York, 1992), Vol. 36.

Chapter Length Overviews/Review Articles

P. M. Amirtharaj and D. G. Seiler, "Optical Properties of Semiconductors" in *Handbook of* Optics, Vol. II, 2nd Edition, M. Bass, E. W. Van Stryland, D. R. Williams, and W. L. Wolfe, eds. (McGraw-Hill, New York, 1995), Chapter 36.

W. M. Bullis, "Oxygen Concentration Measurement" in *Oxygen in Silicon*, F. Shimura, ed. (Academic Press, Inc. Boston, 1994), Chapter 4.

T. H. DiStefano, "Scanned Photovoltage and Photoemission" in *Nondestructive Evaluation of Semiconductor Materials and Devices*, J. N. Zemel, ed. (Plenum, New York, 1979), Chapter 9.

P. F. Kane and G. B. Larrabee, *Characterization of Semiconductor Materials* (McGraw-Hill, New York, 1970).

E. C. Lightowlers, "Photoluminescence Characterisation" in *Growth and Characterisation of Semiconductors*, R. A. Stradling and P. C. Klipstein, eds. (Adam Hilger, Bristol, 1990), pp. 135-163.

R. C. Newman, "Localised Vibrational Mode Spectroscopy of Impurities in Semiconductor Crystals," in *Growth and Characterisation of Semiconductors*, R. A. Stradling and P. C. Klipstein, eds. (Adam Hilger, Bristol, 1990), pp. 105-117.

E. D. Palik and R. T. Holm, "Optical Characterization of Semiconductors" in *Nondestructive Evaluation of Semiconductor Materials and Devices*, J. N. Zemel, ed. (Plenum, New York, 1979), Chapter 7.

S. Perkowitz, D. G. Seiler, and W. M. Duncan, "Optical Characterization in Microelectronics Manufacturing," J. Res. Natl. Inst. Stand. Technol 99, 605-639 (1994).

D. K. Schroder, "Optical Characterization" in *Semiconductor Material and Device Characterization* (John Wiley & Sons, New York, 1990), Chapter 9.

Proceedings

R. A. Alfano, ed., *Ultrafast Lasers Probe Phenomena in Bulk and Microstructure Semiconductors, Proc. SPIE 793* (SPIE, Bellingham, 1987).

R. A. Alfano, ed., *Ultrafast Lasers Probe Phenomena in Bulk and Microstructure Semiconductors II, Proc. SPIE 942* (SPIE, Bellingham, 1988).

D. E. Aspnes, S. So, and R. F. Potter, eds., *Optical Characterization Techniques for Semiconductor Technology, Proc. SPIE 276* (SPIE, Bellingham, 1981).

J. W. Baars and R. E. Longshore, eds., *Future Infrared Detector Materials, Proc. SPIE 1106* (SPIE, Bellingham, 1989).

J. L. Benton, G. N. Maracas, and P. Rai-Choudhury, eds., *Diagnostic Techniques for Semiconductor Materials and Devices*, Proceedings Volume 92-2 (The Electrochemical Society, Pennington, NJ, 1992).

L. J. Brillson and F. H. Pollak, eds., *Surface and Interface Analysis of Microelectronic Materials Processing and Growth, Proc. SPIE 1186* (SPIE, Bellingham, 1989).

N. Cheung and M.-A. Nicolet, eds., *Materials Characterization,* MRS Symposia Proceedings Volume 69 (Materials Research Society, Pittsburgh, 1986).

O. J. Glembocki, F. H. Pollak, and F. Ponce, eds., *Spectroscopic Characterization Techniques for Semiconductor Technology III, Proc. SPIE 946* (SPIE, Bellingham, 1988).

O. J. Glembocki, J. J. Song, and F. H. Pollak, eds., *Modern Optical Characterization Techniques for Semiconductors and Semiconductor Devices, Proc. SPIE 794* (SPIE, Bellingham, 1987).

O. J. Glembocki, S. W. Pang, F. H. Pollak, G. M. Crean, and G. Larrabee, eds., *Diagnostic Techniques for Semiconductor Materials Processing*, MRS Symposia Proceedings Volume 324 (Materials Research Society, Pittsburgh, 1994).

D. C. Gupta, ed., *Silicon Processing*, ASTM STP 804 (American Society for Testing and Materials, Philadelphia, 1983).

D. C. Gupta, ed., *Semiconductor Processing*, ASTM STP 850 (American Society for Testing and Materials, Philadelphia, 1984).

D. C. Gupta and P. L. Langer, eds., *Emerging Semiconductor Technology*, ASTM STP 960 (American Society for Testing and Materials, Philadelphia, 1987).

D. C. Gupta, ed., *Semiconductor Fabrication—Technology and Metrology*, ASTM STP 990 (American Society for Testing and Materials, Philadelphia, 1989).

J. R. Izatt, ed., *Far-Infrared Science and Technology, Proc. SPIE 666* (SPIE, Bellingham, 1986).

B. J. Kolbesen, D. V. McCaughan, and W. Vandervorst, eds., *Analytical Techniques for Semiconductor Materials and Process Characterization*, Proceedings Volume 90-11 (The Electrochemical Society, Pennington, NJ, 1990).

P. H. Langer and W. M. Bullis, eds., *Proceedings of the International Workshop on Process Control Measurements for Advanced IC Manufacturing*, Austin, Texas, November 9-10, 1992 (SEMI, Mountain View, 1992).

E. Passaglia, R. R. Stromberg, and J. Krueger, eds., *Ellipsometry in the Measurement of Surfaces and Thin Films*, NBS Misc. Publ. 256 (1964).

F. H. Pollak and R. S. Bauer, eds., *Spectroscopic Characterization Techniques for Semiconductor Technology I, Proc. SPIE 452* (SPIE, Bellingham, 1983).

F. H. Pollak, ed. *Spectroscopic Characterization Techniques for Semiconductor Technology II, Proc. SPIE 524* (SPIE, Bellingham, 1985).

T. J. Schaffner and D. K. Schroder, eds., *Diagnostic Techniques for Semiconductor Materials and Devices*, Proceedings Volume 88-20 (The Electrochemical Society, Pennington, NJ, 1988).

D. K. Schroder, J. L. Benton, and P. Rai-Choudhury, eds., *Diagnostic Techniques for Semiconductor Materials and Devices*, Proceedings Volume 94-33 (The Electrochemical Society, Pennington, NJ, 1994).

R. D. Westbrook, *Lifetime Factors in Silicon*, ASTM Special Publication 712 (American Society for Testing and Materials, Philadelphia, 1980).

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