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Spectroscopic ellipsometry — Past, present, and future

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ABSTRACT

Since its initial development in the early 1970s, spectroscopic ellipsometry (SE) has evolved to become the primary technique for determining the intrinsic and structural properties of homogeneous and inhomogeneous materials in bulk and thin-film form, including properties of surfaces and interfaces. As an indispensible nondestructive approach for determining critical dimensions in integrated-circuit technology, its economic impact has been enormous. I review the development of theory as well as instrumentation, from the perspective of someone who has worked in SE essentially from its beginning. I provide comments about its present state, note some unresolved issues, then consider possible improvements and predict how the field is likely to evolve.

Contents

1. Introduction

Ten years ago I was privileged to write a similar review [1] for the Third International Conference on Spectroscopic Ellipsometry (ICSE-3), held in Vienna. Since that time progress has been remarkable, and given the essential metrological contributions of spectroscopic ellipsometry (SE) to integrated-circuit (IC) technology, with annual revenues last year of $291.6 B [2], its economic impact has been immense. In that

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review I noted that the main driving force for advancing SE, particularly regarding instrumentation and analysis, was IC technology. The reason was obvious. As Zollner noted in his recent review [3], fabrication of current ICs requires hundreds of steps, including about 100 thickness measurements. About 80 of these are done by SE. While the cell phones, high-performance computers, and cheap data-storage memory that we now take for granted are the combined result of advances in many areas of science and technology, it is no exaggeration to say that these capabilities would not exist in their present form without SE to ensure that these complex processes are maintained within specification. Thus there is no question that SE has had a huge impact on our daily lives.

Moreover, an examination of the issues discussed in ICSE-3 reveal that many of them are now largely behind us. In ref. [1] I listed four: the need to increase accuracy from ±1% to ±0.1%; the need to extend spectral ranges both into the ultraviolet (UV) and infrared (IR); the need for parallel data acquisition and analysis; and the need to use Mueller-matrix ellipsometry (MME) to extract the maximum amount of information from increasingly complex samples. Rotating-compensator ellipsometers (RCEs) and phase-modulator (PEM) ellipsometers now perform well past the target level proposed in the first need and have relegated the rotating-analyzer (RAE) and rotating-polarizer (RPE) ellipsometers to history. As shown by the work presented at ICSE-6, more and more data are being obtained at wavelengths that would have been considered impossible even as recently as 15 years ago. Photodiode-array (PDA) detectors are now in widespread use. MME is now thoroughly established. In addition, competition among well over a dozen vendors, many who had representatives at ICSE-6, remains keen. A number of comprehensive reviews have appeared to supplement the 1977 classic of Azzam and Bashara [4], for example the collection of monographs edited by Irene and Tompkins [5], the comprehensive book by Fujiwara [6], the summary of IR ellipsometry by Schubert [7], and a second collection of monographs edited by Losurdo and Hingerl [8]. The Losurdo and Hingerl volume treats applications of SE to nanostructures, an area that has expanded significantly since 2003. The field is clearly resting on a solid foundation.

But we can also say that the field we call SE has now matured. A look at the many exciting papers presented here shows that the driving force is science. Applications continue to expand, with SE making contributions in nontraditional fields. Much of the work presented here could not have even been imagined when the field got underway in the 1970s. Evidence of maturity is seen in Fig. 1, which is an update of Fig. 2 of the 2003 article [1]. The data show the number of papers published each year with “ellipsometry” as a topic. By 2005 the rapid increase that occurred between 1990 and 2000 had leveled off, and the spikes associated with the 5 previous ICSE meetings (Paris, 1993; Charleston, 1997; Vienna, 2003; Stockholm, 2007; Albany, 2010) are relatively less prominent. However, to put the situation in better perspective, Fourier Transform Infrared Spectroscopy (FTIR) and Raman spectroscopy (Raman) generated 8000 and 12,000 papers, respectively, in 2012. Vibrational spectroscopies provide important information on an atomic scale, but in the appropriate contexts, macroscopic information such as dielectric functions and film thicknesses is more useful. After all, the primary optical diagnostic for IC technology is SE, not FTIR or Raman scattering.

Nevertheless, there remains room for improvement. The objective of spectroscopy, and of SE in particular, is information. By viewing the field from this perspective, we get a better picture of the present and better insight as to where to go in the future. I adopt this perspective throughout.

2. Past

Some of the following material was included in the 2003 review [1], but some repetition is probably acceptable given the large number of new workers in the field. Moreover, ref. [1] was as much a discussion of system transfer functions and the relation of Mueller matrices to Jones matrices as a review. However, I will minimize overlap and also add some personal observations regarding my perception of how SE evolved the way it did, given that I have been active in SE since its beginning.

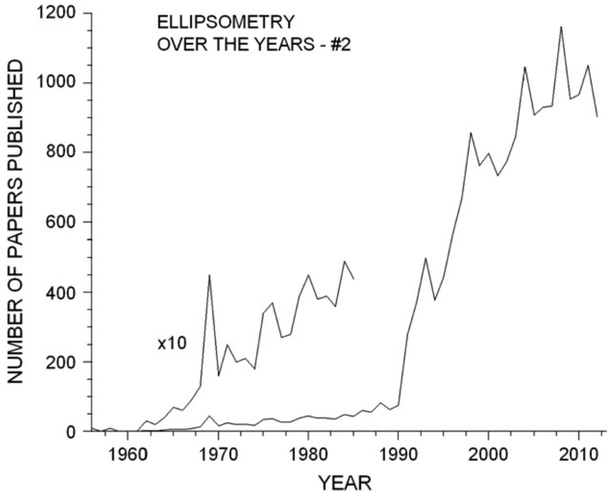

Fig. 1. Number of papers published each year with “ellipsometry” as a topic.

2.1. Technology

Excellent histories of the background and early contributions to ellipsometry have been given by Hall [9], Vedam [10], and Azzam [11]. As noted by Azzam [11], ellipsometry is generally considered to have started with the work of Drude [12,13] in the late 1800s. Drude clearly recognized that measurement and analysis of polarization states instead of intensities offered distinct advantages with respect to both capabilities and accuracy. By referencing the p- to the s-polarized component (TM- and TE-polarized in current terminology), the approach is intrinsically double-beam, with the intensity and its associated inaccuracies removed from consideration. In addition, the relative phase Δ is obtained as a byproduct. The result is the optical analog of an impedance measurement. Using null ellipsometry, Drude determined the optical properties of 18 metals [13]. The term “ellipsometry” was introduced in 1945 by Rothen [14], who at the same time discussed a half-shade method of improving sensitivity to the setting yielding zero intensity in null ellipsometers. However, the first paper with “ellipsometry” in the title was not published until 1958 [15].

Until about 1975 most ellipsometric measurements were done using the null configuration. For the benefit of the present generation, many of whom probably never heard of null ellipsometry, seen a null ellipsometer, or almost certainly have never operated one, the configuration consists of an entrance arm that contains a polarizer set at an azimuth angle P relative to the plane of incidence, and ideally a quarter-wave plate of relative retardation 90° and azimuth angle $C = 45°$. The exit arm contains a second polarizer, termed the analyzer, set at an azimuth angle A. Its system transfer function illustrates the origin of the (tanψ, cosΔ) notation and highlights the problems associated with its operation:

$$\frac{E_{\mathrm{det}}}{E_{source}} = \frac{\sin A}{\sqrt{2}r_s}\left(\left(\tan\psi\ \cot A\right)e^{i(\Delta-2p)}+1\right), \qquad (1)$$

where in the usual notation the complex reflectance ratio $\rho = r_p/r_s = (\tan\psi)e^{i\Delta}$. The objective is to use P to adjust the ellipticity of light incident on the sample such that the net phase shift is 180°, leaving the reflected beam in a linearly polarized state, in which case E_{det} reaching the detector (typically your better eye) can be extinguished by suitably adjusting A. By Eq. (1) this occurs for $A = \Psi$ and $P = 90° - \Delta/2$. The

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