特集論文
FEATURE ARTICLE

Full Automatic Spectroscopic Ellipsometer UT-300

Part 2 Basic Principles of Ellipsometry and PEM

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Abstract

With increasing semiconductor device integration, many layers thickness is shrinking below 10-100 Å. The precise control of layers thickness and materials characterization has thus become a major concern. This trend explains how Spectroscopic Ellipsometry has spread within 10 years from Research Labs to most semiconductor fabs. As an optical technique, it is non destructive, and can be employed on product wafers. And it has unequalled capabilities for thin film characterization.

JY's spectroscopic ellipsometer is based on the use of a PEM modulator, which allows fast and accurate measurements. The optical system combines with a powerful numerical data acquisition system, that enables real time multiple wavelength computing. We compare JY's technology with other systems, such as rotating polarizer type of ellipsometer. As detailed in another paper from this serie, PEM ellipsometer proves to be the most sensitive and precise technique for ultra thin films measurements.

要 旨

半導体デバイスの集積度が上がるにしたがい，1～10nm以下の非常に薄い薄膜の精密な膜厚制御や特性評価に関心が集中している。この傾向は，以前は主に研究室で使われていた分光エリプソ法が，ここ10年の間にほとんどの半導体生産現場に導入されている事実からも明らかである。これは，光学的な測定原理に基づき非破壊検査が可能な本法は，生産ラインのウエハを直接検査することができ，しかも他に匹敵し得る評価法が見当たらないためである。

ジョバンイボン社（JY）の分光エリプソメータは，フォトエラスティク・モジュレータ（PEM）を使った位相変調方式を採用しており，高速で正確な測定ができる。強力なデータ採取システムを一体化した光学系により，多波長のリアルタイム演算が可能である。本機は，回転偏光子型のエリプソメータを凌ぐ，超薄膜用として最も感度が高く，高精度である。

1 Spectroscopic Ellipsometry

Ellipsometry is an optical technique used for Thin Films thickness metrology. Spectroscopic ellipsometers have recently emerged as powerful tools in the semiconductor and flat panel display fabrication, because such instruments are capable of non destructive in line characterisation of multilayers thin films stacks deposited on silicon substrates.

Based on the measurement of the change in light polarization upon reflection from a sample surface, ellipsometry derives thin films thickness and optical properties (refractive index and absorption coefficient) with extreme accuracy. The spectroscopic capability allows for simultaneous determination of multiple parameters : for example multilayer thickness and composition of thin film stacks.

Ellipsometry means measuring an ellipse, unfortunately this ellipse of polarization is not visible to human eye. Light arises from electro-magnetic vibrations and is described not only by its colour (or wavelength), intensity, but also by its polarization. If we could see a linearly polarized light reflecting from a flat surface, it would appear elliptically polarized after reflection. Indeed, the two components of the electromagnetic field, one"in the plane of incidence" (p), and the other perpendicular (s) to the plane of incidence, experience different attenuation and phase shift at the reflection (Fig.1). Ellipsometry measures the ratio of these reflection coefficients, and is usually described by a set of two data, Psi and Delta :

$$\rho = r_p/r_s = \tan(\Psi) . \exp(i.\Delta)$$

As r_p and r_s are linked to the material refractive index (through Fresnel's law), the materials optical properties can be derived as a function of the recorded wavelength. So, measuring the ellipse can indirectly give us informations about the surface it reflects from. Spectroscopic measurements, by recording Ψ and Δ as a function of the wavelength, give information about materials dispersion and absorption.

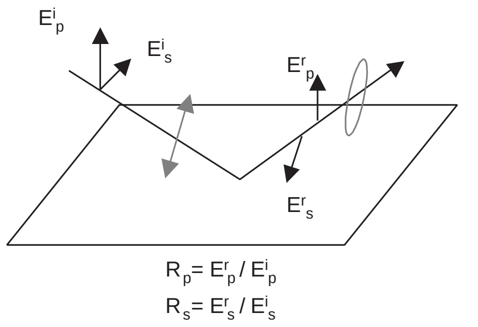

Fig.1 Principle of ellipsometry

2 Different Modulated SE Techniques

In metrology tools, signal modulation is commonly used to speed up data acquisition while improving Signal to Noise ratio.

An ellipsometer is made by illuminating a sample with polarized light under oblique angle of incidence : a first polarizer is placed before the sample to define initial polarization, and another polarizer (usually called analyzer) placed in front of the detector to analyze beam polarization after reflection onto the sample. Different setups can include additional elements.

There are different solutions to modulate light polarization : one is by mechanically rotating one of the polarizers (Fig.2), which modulates the direction of polarization, the other by inserting a Phase Modulator (or PEM), that modulates the phase of the polarization, by periodically transforming the input linear polarization into an elliptical polarization (Fig.3).

What are the advantages and drawbacks of each technique ?

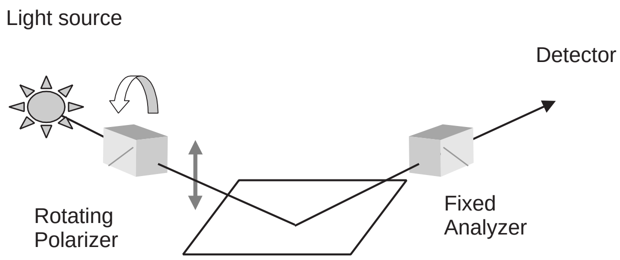

Fig.2 Rotating Polarizer type of ellipsometer

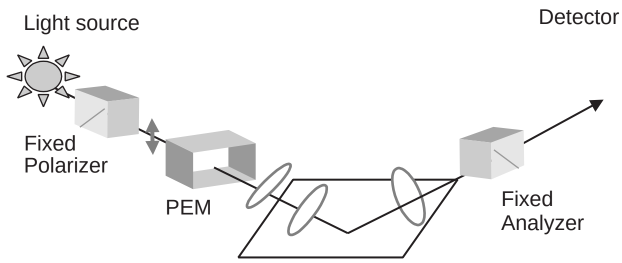

Fig.3 Phase Modulated Ellipsometer

全自動超薄膜計測システム UT-300
Part 2 分光エリプソメトリの原理と PEM

1 分光エリプソメータ

半導体やFPDなど生産現場において，分光エリプソメトリは，多層薄膜の光学的特性評価法として近年とみに重要性が増している。

分光エリプソメータ（SE）は，薄膜表面から反射光の偏光状態の変化から膜厚と光学特性（屈折率，減衰係数）を高精度に算出する装置で，多層膜の膜厚や組成などの多数のパラメータを同時に求めることができる。

電磁波（光）は，色（波長）と強度だけではなく偏光状態でも記述される。平坦な表面で反射した直線偏光は楕円偏光となる。電磁波には入射面内にある成分（p）と入射面に垂直な成分（s）の２成分があり，反射による減衰と位相変化はそれぞれの各成分で異なる（Fig.1）。

SEでは，これら2成分の反射係数の比（r）を測定する（式）。

分光器でΨとΔを波長の関数として測定し，物質の分散と減衰に関する情報を得る。

2 SEの変調方式

計測機器では，SN比の向上のために，信号に変調をかけて高速でデータをサンプリングする。SEでは偏光をサンプルに対して斜めに入射させる。入射側には第一の偏光子が，出射側には第二の偏光子（検光子）が置かれる。

SEにおける光変調にはいくつかの方法がある。一つは，偏光子を機械的に回転させる方法（Fig.2）で，もう一つは，位相変調器（PEM）を用いて直線偏光を楕円偏光に周期的にする方法（Fig.3）である。

2.1 Rotating Polarizer / Rotating Analyzer Types : Simple, but Slow and Inaccurate

Rotating a polarizer at constant speed is a simple technique : it does not need additional elements, and modulation is the same for all wavelengths. However, measurements are relatively slow, limited by mechanical rotation speed (few 10 or 100 Hertz). In addition, such modulation frequencies fall within noise range from other mechanical devices, that can perturb data acquisition. Also, such systems are affected by source or detector residual polarisation sensitivity, or by polarizer inhomogeneities over the beam rotation. Such imperfections can partially be reduced by a calibration, but they can drift with time, thus introducing errors.

Signal equations from a rotating type ellipsometer provide functions of Tan(Ψ) and Cos(Δ) : Δ precision is low, in the regions where Δ = 0 (180°). As it turns out that Δ is the most sensitive parameter to small changes, such as from ultra thin films, Δ precision is extremely important to determine ultra thin films.

2.2 PEM : Fast and Accurate

JY's PEM ellipsometer combines two key elements : phase modulation and an entirely numerical data acquisition and processing system. These features allow for a robust design with no mechanically moving parts, and for rapid and precise measurements.

The PEM is a transparent quartz bar (Fig. 4), to which is applied a sinusoidal vibration, though piezo-electric elements : an electrical signal is applied to piezo electric transducers that induces mechanical strain and is transfered from the piezzo to the quartz bar. This mechanical strain induces a periodical birefringence into the quartz bar. When polarized light is going through the modulator, it is affected by the modulated birefringence, and as a result the two components undergo a modulated phase shift : an input linearly polarized beam becomes elliptically polarized at the output of the modulator, and the size of the ellipse is modulated at the frequency of modulation. This modulation is performed without any mechanical movement, resulting in improved signal stability and accuracy. Signal equations provide tan(Δ) and cos(2.Ψ) : Δ precision is thus excellent over the whole range.

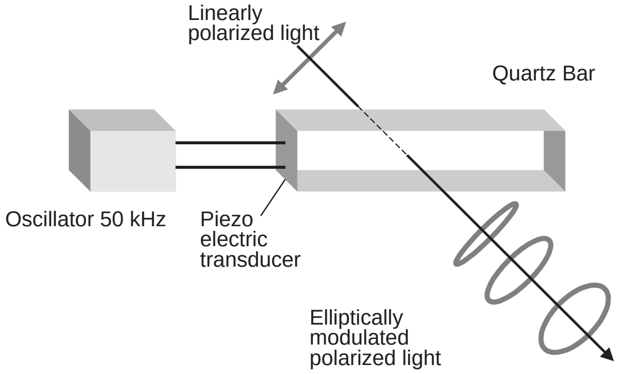

Fig.4 Principle of Photo-Elastic Modulator

The PEM high frequency modulation (50 kHz) allows fast measurement, with minimum 5 ms acquisition time. The fast electronic acquisition filters out noise due to low frequency vibrations which results in higher signal to noise ratio than Rotating Polarizer modulation. Because it results from a sustained oscillation, each PEM frequency is fixed by the bar length and thus extremely stable (less than few Hertz jitter). In addition, our new real time multichannel data acquisition system can perform simultaneous measurements over multiple wavelengths, without increasing integration time.

2.1 回転偏光子／回転検光子型：シンプルだが応答が遅く，不正確

このタイプは，構成がシンプルで，全波長にわたり同じ変調方式が可能である。しかし，測定時間が長く，他の機械部品の振動により測定精度が低下する欠点がある。もちろん，光源や検出器の感度，偏光子の不均一性などの影響も受ける。

本方式の状態式は，Tan（Ψ）と Cos（Δ）で表すことができ，Δ =0, 180 °の時にはΔの精度が低下する。つまり，超薄膜の場合には，わずかしか変化しないΔの精度が極めて重要となる。

2.2 PEM：速くて正確

JY の PEM/SE は，位相変調をかけ，全ての数値データ採取・処理・処理手段を組み合わせ，可動部のない設計をしたことにより，高速で正確な測定が実現できた。

PEMは透明な石英板に圧電殿素子を貼り付けたもので，これに正弦状の電圧を印加させると周期的に複屈折が生じる。直線偏光は PEM を通過すると，複屈折により p, s 二つの成分で位相差が生じ，楕円偏光となる。PEM には可動部分が全くないため,安定で正確な信号が得られる。出力からは tan（Δ）と cos（2.Ψ）が得られれる。Δの精度は全波長にわたり優れている。

高周波数変調された PEM（50KHz）では最高 5ms の高速測定が可能となった。これにより，低周波数ノイズを除き，回転型偏光方式に比べて高い SN 比を実現した。

PEM requires a more careful control that a rotating polarizer, but Jobin-Yvon has acquired this knowledge, as PEM are used in JY's dichrographs for more than 20 years. The amplitude of modulation is calibrated from fabrication versus electrical signal, and versus wavelength. Modulation is internally controlled, so as to provide easy and extremely stable measurements. This requires in particular, a good PEM thermal stability.

As a result JY's PEM SE (Fig.5) are classed the most accurate spectroscopic ellipsometers, with excellent S/N ratio, over the whole UV-visible range (190-850 nm.).

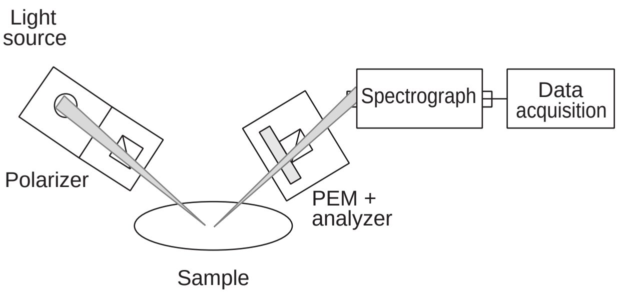

Fig.5 Jobin-Yvon PEM ellipsometer setup

3 Conclusion

The PEM technological advantage is combined with our expertise in materials characterization and thin films analysis, to provide high performance characterization techniques in the semiconductor thin film industries. As detailed in another paper from this serie, PEM ellipsometer proves to be the most sensitive and precise technique for ultra thin films measurements.

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さらに，マルチチャネル・データサンプリングシステムを採用し，積算時間を長くとらなくても，多波長のリアルタイム測定が可能となった。

PEMは回転型よりも厳密な制御が必要となるが，JYでは20年以上にわたるダイクログラフ技術の蓄積により解決している。変調の振幅は製造段階で正確に校正されており，また，内部回路で自動制御されているため，極めて安定な測定が可能である。

以上の技術をベースとして，JY の PEM/SE（Fig.5）は190-850nm の波長全領域で最高の性能を有している。

3 おわりに

以上，PEM の優位性と，材料特性評価ならびに薄膜解析のノーハウとをうまく融合させた，JY の分光エリプソメータの概要を述べた。本PEM エリプソメータが，より高感度で高精度な超薄膜測定ができる点については，機を改めて詳しく述べる。

（抄訳 編集部）