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POLARIZATION-ENTANGLED PHOTON PAIRS OBVIATE NEED FOR CALIBRATION IN MATERIAL CHARACTERIZATION

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Quantum entanglement is a peculiar aspect of quantum mechanics that has baffled physicists and philosophers alike. Until recently, it has exclusively been used in many experiments to study the foundations of quantum mechanics. We show how entanglement can be harnessed to obtain ellipsometric data from materials without the need for calibration.

1 Introduction

Ellipsometry[1] is a well-established metrological technique used, particularly in the semiconductor industry, to determine the thickness and optical constants of thin films. The high accuracy required in measuring these parameters necessitates absolute calibration of both the source and the detector. As this is not attainable in practical settings, all ellipsometric techniques employ a reference sample for calibration.

In this paper, we show how quantum ellipsometry alleviates the aforementioned problem by using a two-photon polarization-entangled state generated by type-II spontaneous parametric downconversion (SPDC).[2,3] This is done in a simple setting with a minimal number of optical components.[4,5]

The quantum ellipsometer is illustrated in Fig. 1. A 406-nm cw Kr^+ laser (pump) beam illuminates a nonlinear optical crystal (NLC), beta-barium borate. Quantum mechanics predicts that some of the pump photons disintegrate into pairs, known as signal and idler, which conserve energy (frequency-matching) and momentum (phase-matching).[3,6] For our purposes, we choose the SPDC to be in a configuration known as 'type-II non-collinear'. 'Type-II' refers to the fact that the signal and idler photons have orthogonal polarizations; the term 'non-collinear' indicates that the signal and the idler photons are emitted in two different directions. The idler beam reflects off the sample of interest before it encounters a linear polarizer (A_1) followed by single-photon photodetector (D_1). The signal beam encounters a linear polarization analyzer (A_2), followed by a single-photon photodetector (D_2). The detectors, two avalanche photodiodes operating in the Geiger mode, are part of a circuit that records the coincidence rate of photon pairs. The sample is characterized by the parameters ψ and Δ: ψ is the ratio of the magnitudes

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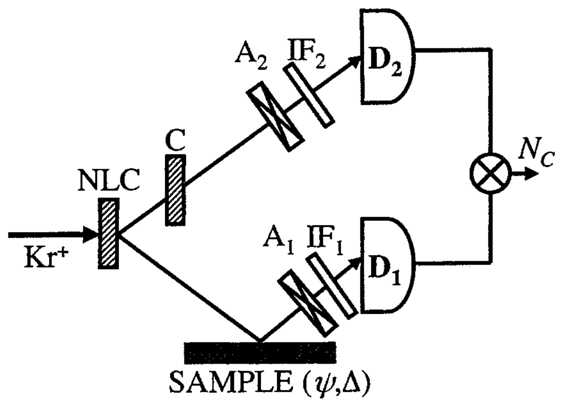

Figure 1. Polarization-entangled twin-photon ellipsometer. NLC stands for nonlinear crystal; C is a birefringent compensator; A_1 and A_2 are linear polarization analyzers; IF_1 and $IF2_2$ are interference filters; D_1 and D_2 are single-photon detectors; and N_c is the coincidence rate. The sample is characterized by the ellipsometric parameters ψ and Δ defined in the text.

of the sample reflection coefficients, R_H and R_V for the *p*- and *s*-polarized waves, respectively; Δ is the phase shift between them.

In order to select the degenerate twin photons centered at 812 nm, interference filters (IF_1 and IF_2) with 10-nm bandwidths were placed in front of each detector. Because of the birefringence of the NLC used to generate SPDC, the signal and idler photons emerge from the NLC with a relative time delay that one compensates for by placing an appropriate birefringent material (labelled C in Fig. 1) of suitable thickness in the signal and/or idler path.[2]

The non-classical source and the optical arrangement shown in Fig. 1 exhibit two features that circumvent the two problems noted above, i.e., calibration of the source and of the detector. The first characteristic of quantum ellipsometry is that the source is a twin-photon source; i.e., we are guaranteed on detection of a photon in one of the arms of the setup that its twin is in the other. The second characteristic is the polarization entanglement of the source. Polarization entanglement acts as an interferometer, encompassing both arms of our apparatus, thereby alleviating the need for calibrating the second detector in our coincidence scheme.[4,5]

It can be shown that the measured coincidence rate, N_c, is given by[4,5]

$$\begin{aligned} N_c = C[&\tan(\psi)\cos^2(\theta_1)\sin^2(\theta_2) + \sin^2(\theta_1)\cos^2(\theta_2) \\ &+2\sqrt{\tan(\psi)}\cos(\Delta)\cos(\theta_1)\cos(\theta_2)\sin(\theta_1)\sin(\theta_2)], \end{aligned} \tag{1}$$

where the constant of proportionality C depends on the efficiencies of the

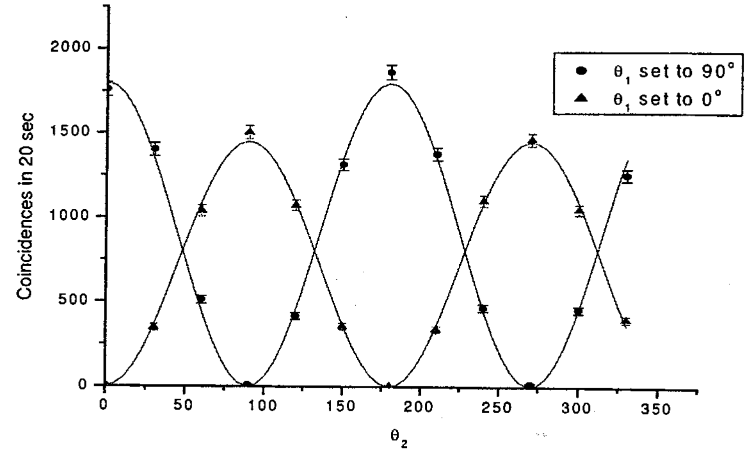

Figure 2. Interference patterns obtained from an experiment on a silicon sample.

detectors and the duration of accumulation of coincidences.[5]

2 Experimental Results

Preliminary experiments have shown that polarization-entangled photon pairs can be used to obtain values of ψ that are comparable to those obtained from traditional ellipsometers.

Using the experimental setup described earlier, a silicon (Si) sample was tested at an angle of incidence of 30°. First, the angle of the analyzer A_1, denoted θ_1, was set to 90° while θ_2 was scanned. Referring to Eq. (1), which, for θ_1=90°, reduces to

$$N_c = C\cos^2(\theta_2), \tag{2}$$

reveals that the amplitude of this curve provides the value for C. Second, θ_1 was set to 0° while θ_2 was again scanned. In this case, Eq. (1) reduces to

$$N_c = C[\tan(\psi)\sin^2(\theta_2)], \tag{3}$$

so that the amplitude of this function is equal to $C\tan(\psi)$. The resulting interference patterns are shown in Fig. 2. One can therefore determine ψ simply by dividing the two functions. Using this approach, ψ was determined to be $40.2 \pm .1°$ for our Si sample. The expected value for ψ at this angle of incidence is 40.4° in accordance with calculations carried out using the appropriate Sellmeier dispersion formula.[7,8]

Unfortunately, the interference patterns obtained using a technique similar to the one described above did not provide a reasonable value for Δ.

The main reason for this comes from the fact that the equations used to obtain ψ assumed that the quantum state of the light emitted by the NLC is a maximally-entangled pure state. In order to obtain Δ, Eq. (1) must include the dependence of the ellipsometric parameters on the actual state of the light that is available in practice.

3 Conclusion

We have shown that, by employing entangled-photon pairs that are generated by type-II SPDC in a non-collinear configuration, one can obtain absolute ellipsometric data from a reflective sample. The underlying physics that permits such ellipsometric measurements resides in the fact that fourth-order (coincidence) quantum interference of the photon pairs, in conjunction with polarization entanglement, emulates an idealized classical ellipsometric setup that utilizes a source and a detector that are both calibrated absolutely.

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