Optical Layer Systems for Product Authentication: Interference, Scattering, Light Diffusion and Ellipsometric Encoding as Public, Hidden and Forensic Security Features

D. Hönig[1], S. Schneider[1], R. Domnick[2], M. Belzner[2],
U. Beck[3], A. Hertwig[3], R. Stephanowitz[3], M. Weise[3]

[1] Accurion GmbH, Stresemannstraße 30, 37079 Göttingen, Germany
[2] Ara-Coatings GmbH & Co. KG, Gundstraße 13, 91056 Erlangen, Germany
[3] BAM Federal Institute for Materials Research and Testing, Division 6.7
Unter den Eichen 87, 12205 Berlin, Germany

uwe.beck@bam.de, Phone/Fax: +49 30 8104 1821/1827

1. Introduction

Embedding of information on surfaces is state of the art for identification testing in which public, hidden and forensic features are used. In many instances, the legal authentication of a product, a material or a document is required. Among the surface-based encoded labels, bar codes and data matrices are most frequently applied. They are publicly visible. The material itself is irrelevant, only a sufficient optical contrast is required.

However, a strong material dependence of the label can be achieved by means of Fabry-Perot layer stacks. Stack designs are described with regard to all three security levels: public features (e.g. color and tilt effect) perceptible by the human eye, hidden features (e.g. optical response in a given spectral range) detectable by commonly available instruments and forensic features (ellipsometric quantities Ψ and Δ as a function of wavelength λ and angle of incidence AOI) only detectable by sophisticated instruments.

Regarding material-correlated authentication, ellipsometric quantities Ψ and Δ are used as encoded forensic features for the first time [1]. Hence, Fabry-Perot layer stacks as information carriers in combination with imaging ellipsometry as optical read-out system provide all-in-one anti-counterfeiting capabilities.

2. Fabry-Perot layer stacks as information carrier

For conventional interference layers, the angle-dependent colour appearance, known as tilt effect, is mainly influenced by the thickness and the refractive index of a dielectric film on a sufficiently high reflecting substrate. Thus, for conventional interference layers, thickness and angular dependence are both unavoidable and desired design features [2-4].

Fabry-Perot layer stacks consist of at least two transparent dielectric layers embedding a semi-transparent metallic thin film in between. The entire layer stack is deposited on a highly reflecting substrate. The coloration effect is now mainly caused by multiple-beam interference within the Fabry-Perot cavity, i.e. within a semi-transparent/transparent/non-transparent metal-insulator-metal (MIM) structure. Fabry-Perot interferences are dominated by the thin semi-transparent metallic film, in particular its thickness and its morphology.

The application of Fabry-Perot stacks and their modifications results in a material-, morphology-, and design-dependence of the label. Instead of contrast in terms of grey scale, all colours (including black and white) can be realised with high brilliance. The dielectric layer on top of the semi-transparent metallic film ensures the long-term stability of the entire layer stack in particular the protection from environmental effects. As shown in Figs. 1 and 2, the design of Fabry-Perot layer stacks can be modified in a way that the angular colour dependence known from conventional interference layers remains preserved (tilt effect) or vanishes (Aradierung®).

Fig. 1: Colour appearance of a Fabry-Perot stack (SiO_2-Cr-SiO_2 on Al) with tilt effect; dependence on AOI and design features: normal incidence (upper line), AOI = 45° (centre line) and AOI = 60° (lower line); design A (left column), design B (centre column), design C (right column)

The angle-independence of colour is achieved by specific multi-material designs and process modifications affecting the morphology of the semi-transparent metallic film.

Fig. 2: Colour appearance of Fabry-Perot stacks without any tilt effect (Aradierung®)

The light diffusion effect (LDE) as superimposed scattering effect is caused by different grain textures of the metallic interlayer and depends on the angle of incidence and the spectral range of illumination. The result is a colour change upon reflection (Ara-Authentic®) as shown in Fig. 3.

Fig. 3: LDE-effect of Fabry-Perot stacks upon reflection (Ara-Authentic®)

Thus, Fabry-Perot layer stacks and their modifications *per se* provide features of all security levels. Moreover, they are suitable for the generation of pattern such as 1D- and 2D-bar codes. This can be realised either by laser modification of the semi-transparent metallic interlayer or the bottom reflector. In case of complete or almost complete removal of the bottom reflector, effects in transmission can also be achieved.

3. Imaging ellipsometry as optical read-out technique

Regarding light intensity, ellipsometry is a standard-free phase-sensitive far-field tech
A. Hertwig[3], R. Stephanowitz[3], M. Weise[3]nique with polarised light upon reflection. An ellipsometric measurement is defined as a measurement at *one* defined AOI and at *one* wavelength λ. Due to the p- and s-polarisation dependence on boundary

conditions, *two* quantities, i.e. the amplitude ratio Ψ and the phase shift Δ, can be derived. In terms of ellipsometric encoding, λ and AOI serve as external key and Ψ and Δ as optical system response of the native (as engineered) or artificial (as designed) surface. Even the interlinking of native and artificial surfaces is feasible [1]. Spectroscopic (from the UV to the NIR spectral range) and angular (typically from 30° to 80°) dependent measurements provide a huge number of external keys.
Using imaging ellipsometry based on null-ellipsometry, Ψ- and Δ-images of the surface are available from the beginning. Hence, the recognition of pattern such as 1D- and 2D-bar codes (Fig. 4) is also feasible. By an imaging microscope ellipsometer (nanofilm-ep4se), spatial resolutions down to 1 µm can be reached and hence bar code-in-bar code solutions become readable on both the macroscopic and the microscopic scale.

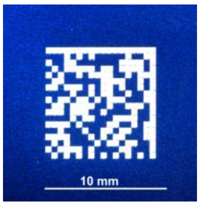

Fig. 4: Data matrix made from a Fabry-Perot stack (available as video-,Ψ- and Δ-image)

The optical system response of the native or artificial surface in Ψ and Δ is theoretically limited to 0°≤ Ψ ≤ 90° and -180° ≤ Δ ≤ +180° whereas the accuracy of measurement in Ψ and Δ is about 0.1°. This fact justifies the high surface sensitivity of ellipsometry, e.g. on native oxides, surface roughness or humidity films. For authentication, this circumstance is rather counterproductive as real surfaces are usually subject to certain variations in surface quality and hence the ellipsometric quantities vary to some extent. A sufficiently high insensitivity to these variations is therefore required. A rounding in steps of 10° for Δ should guarantee the recognition of a Δ-value as encoded. The available set of values would then amount to 360 : 10 = 36 symbols. This equals to the number of all alphanumeric signs and is more than twice as much as the hexadecimal code would require. Information storage based on the value of Δ enables designs that are not visible for the naked eye as the human eye is not sensitive to polarisation.
In contrast to native surfaces where the Ψ- and Δ-values over wavelength and angle of incidence have to be taken as given features of the surface as engineered, artificial surfaces, in particular Fabry-Perot stacks, provide for the feasibility to design layer systems with the full theoretical Δ-range, i.e. 360° either in dependence on a defined wavelength (Fig. 5) or angle of incidence range. This is the reason why Fabry-Perot stacks are the layer systems of choice regarding ellipsometric encoding.

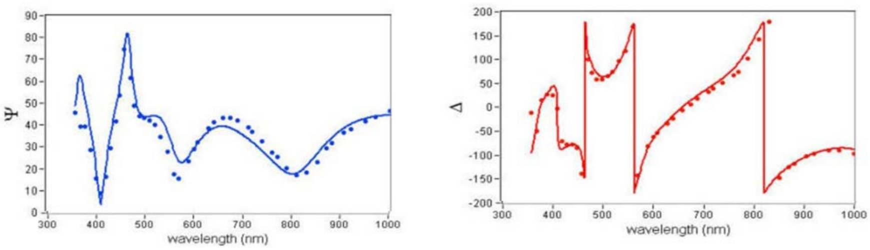

Fig. 5: Forensic features Ψ (amplitude information) and Δ (phase information) as a function of λ at given AOI

The use of λ and AOI as external keys and the application of Δ (and Ψ) as encoding table in combination with specially designed Fabry-Perot stacks might give access to a further security level *encoded forensic*. Cryptographic or steganographic features or information can be additionally implemented, also by using the ellipsometric quantities. Despite these facts, all security levels such as *public*, *hidden*, *forensic,* and *encoded forensic* can be realized at the same time with one individual Fabry-Perot layer stack in terms of PUF-functions.

4. Summary and outlook

Fabry-Perot layer systems may be carrier of public, hidden and forensic information. Physically uncloneable functions (PUFs) are realized by means of parameter-based forward stack designs, complex multi-material approaches in the deposition process and technology-dependent intrinsic preparation characteristics.

Ellipsometry is a phase-sensitive forensic measurement technique in the optical far field which assigns the ellipsometric quantities Ψ and Δ to any native and artificial surface depending on the angle of incidence (AOI) and as a function of wavelength. This can be used for ellipsometric encoding, i.e. the interlinking of information, security labels, and the product itself. The use of encoding tables for the ellipsometric quantities Ψ and Δ allow the embedding of information in dependence on the parameters AOI and wavelength as external keys.

The combination of Fabry-Perot labels as code-carriers and imaging ellipsometry as optical read-out system [5] provides a forensic all-in-one authentication system that may establish the new security level *encoded forensic.*

References

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