Optical Detection
using
Computer Screen Photo-assisted Techniques
and
Ellipsometry

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Cover: “Rotating spectrum” and illustrations of components from setups described in this thesis.

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Gold rush
There once was a polarized light beam
Linearly polarized it might seem
But then it hit gold
The light beam was sold
Dancing in circles the new theme

Inspired by free association and yet another striking similarity between light beams and humans.

To my family
Abstract

Two main subjects, ellipsometry and computer screen photo-assisted techniques (CSPT), form the main line in this thesis. Ellipsometry is an optical technique based on the detection of polarization changes of light upon interaction with a sample. As most optical detection techniques it is non-intrusive and an additional advantage is its high surface sensitivity: thickness resolution in the order of pm can in principle be achieved. Therefore, ellipsometry is widely used as a technique for determination of optical constants and layer thickness for thin-layer structures. Lately ellipsometry has also been proposed for sensing applications, utilizing the detection of changes in the properties of thin layers. One application is described in this thesis concerning the detection of volatile organic solvents in gas phase using modified porous silicon layers, fabricated by electrochemical etching of silicon to create nm-sized pores. This greatly increases the surface area, promoting gas detection because the number of adsorption sites increases. Other applications of ellipsometry discussed in this thesis are based on combination with CSPT.

CSPT is a way to exploit existing optical techniques for use in low-cost applications. In CSPT the computer screen itself is used as a (programmable) light source for optical measurements. For detection a web camera can be used and the whole measurement platform is formed by the computer. Since computers are available almost everywhere, this is a promising way to create optical measurement techniques for widespread use, for example in home-diagnostics. Since the only thing that needs to be added is a sample holder governing the physical or chemical process and directing the light, the cost can be kept very low. First, the use of CSPT for the measurement of fluorescence is described. Fluorescence is used in many detection applications, usually by chemically attaching a fluorescent marker molecule to a suitable species in the process and monitoring the fluorescent emission. The detection of fluorescence is shown to be possible using CSPT, first in a cuvette-based setup, then using a custom designed micro array. In the latter, polarizers were used for contrast enhancement, which in turn led to the implementation of an existing idea to test CSPT for ellipsometry measurements. In a first demonstration, involving thickness measurement of silicon dioxide on silicon, a thickness resolution in the order of nm was already achieved. After improvement of the system, gradients in protein layers could be detected, opening the door toward biosensor applications. Some further development will be needed to make the CSPT applications described here ready for the market, but the results so far are certainly promising.
Included papers

I Improvement of porous silicon based gas sensors by polymer modification
physica status solidi (a) 197, 378-381 (2003)

II Enhancing classification capabilities of computer screen photo-assisted fluorescence fingerprinting
J.W.P. Bakker, D. Filippini and I. Lundström
Sensors and Actuators B: Chemical 110, 190-194 (2005)

III Two-dimensional micro array fluorescence fingerprinting with a computer screen photo-assisted technique
J.W.P. Bakker, D. Filippini, I. Lundström

IV Computer screen photo-assisted off-null ellipsometry
J.W.P. Bakker, H. Arwin, I. Lundström and D. Filippini
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V Non-labeled immunodetection with a computer screen photo-assisted technique
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Other publications not included in the thesis

Optical properties of intrinsic and doped a-Si:H films grown by d.c. magnetron sputter deposition

Linear viscoelastic behavior of enzymatically modified guar gum solutions: structure, relaxations, and gel formation
Macromolecules 34, 6014-6023 (2001)

Determination of refractive index of printed and unprinted paper using spectroscopic ellipsometry
J.W.P. Bakker, G. Bryntse and H. Arwin

Fingerprinting of fluorescent substances for diagnostic purposes using computer screen illumination
D. Filippini, J. Bakker and I. Lundström

New methodology for optical sensing and analysis
J. Bakker
Linköping Studies in Science and Technology Licentiate Thesis number 1090
Linköping University, 2004

Computer screen photo-assisted measurement of intensity or polarization change of light upon interaction with a sample
J.W.P. Bakker, H. Arwin, D. Filippini and I. Lundström
US provisional patent submission US60/733,256
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Chapter 1

Introduction

Through the ages, people have always been fascinated by light and studying its properties. As early as 300 BC, Euclid noted in his *Optica* that light travels in straight lines and he described the law of reflection. With studying of the behavior of light, came also its manipulation. Refraction of light was discovered and put to use and in 1284 the Italian Salvino D'Armate constructed the first wearable eye glasses. In 1590, Dutch eye glass maker Zacharias Janssen experimented with multiple glass lenses placed in a tube and so created the first microscope.

A lot has happened since the invention of the microscope, but still many measurements are based on interaction with light. Nowadays many of those require spectroscopy or monochromatic light and thus high quality lamps combined with monochromators or lasers can be found in a large amount of commonly used optical instruments. These instruments can measure very accurately, in some cases more accurate than needed for a certain application. This is in itself of course not a problem, but if the same result, albeit less accurate, can be achieved by methods that cost only a fraction of the commonly used techniques, this certainly becomes worth researching. This is especially an issue when measurements should be performed outside the laboratory environment. Examples of this are optical sensing and home-based medical testing. In such applications, development is aimed at devices which have as high as possible sensitivity and accuracy, for as low as possible cost.

The optical detection applications described in this thesis are typical examples of this field. The work described in paper I is part of a project developing optical gas sensors based on ellipsometry. Porous silicon, with its high surface area, provides a way to detect low gas concentrations in a relatively cheap and simple setup. Still, sensitivity and selectivity need to be maximized. Modification of the porous silicon by polymer deposition in order to achieve this goal is presented here.

The other papers in this thesis describe work done on Computer Screen Photo-assisted Techniques (CSPT). CSPT is based on using the computer screen as a light source for optical measurements and, if optical readout is required, a web camera as detector. By doing this, regular computer sets become measurement platforms. Since computers are available at almost every home and working place nowadays, potential measurement setups are everywhere and can be adapted for CSPT measurements at very low cost. The primary application which CSPT aims at is home-based medical testing. Starting with the home pregnancy test in 1978, this field has developed much
in the past years. Many home testing kits are based on optical readout, usually color change. This change can be interpreted either by the user directly or by a dedicated electronic reader. The latter are usually more accurate, but highly specialized, which means that a separate reader is needed for every testing application. Here CSPT offers a promising alternative. A range of different tests can be performed using the same platform by only changing the type of sample and sample holder and adapting the software. For this to be as effective as possible, different measurement principles need to be developed for CSPT. Two of these techniques are described in this thesis.

The first measurement principle is detection of fluorescence. Fluorescence is widely used in bioassays by attaching a fluorescent marker to target molecules and monitoring the fluorescent emission, which is either promoted or prevented by the chemical reaction of interest. A setup built to separate the emitted light from the transmitted light by measuring from the side is presented in paper II (a setup measuring fluorescence by detecting transmitted and emitted light together had been published before). In paper III, a custom-made micro well setup is presented, which uses crossed polarizers for eliminating the transmitted light.

The second principle is ellipsometry, a technique using polarized light to measure the properties of materials and particularly optical and microstructural properties of thin layers. This is presented in paper IV for thickness measurements of silicon dioxide layers on silicon. Finally, in paper V a step toward bioapplications is made by presenting an improved setup, which is able to measure antibody-antigen reactions.
Chapter 2

Theory

2.1 Elementary Optics

2.1.1 Interaction of electromagnetic waves with matter

The Maxwell equations [1] give a macroscopic description of the propagation of electromagnetic waves and their interaction with matter:

\[ \nabla \cdot \vec{D} = \rho \]  (2.1)

\[ \nabla \cdot \vec{B} = 0 \]  (2.2)

\[ \nabla \times \vec{H} = \vec{J} - i\omega \vec{D} \]  (2.3)

\[ \nabla \times \vec{E} = i\omega \vec{B} \]  (2.4)

where \( \vec{D} \) is the dielectric displacement, \( \rho \) the charge density, \( \vec{B} \) the magnetic induction, \( \vec{H} \) the magnetic field, \( \vec{J} \) the current density and \( \vec{E} \) the electric field. The behavior of matter when subjected to electromagnetic fields is described by the constitutive equations,

\[ \vec{B} = \mu_0 \vec{H} \]  (2.5)

\[ \vec{D} = \varepsilon_0 \vec{E} \]  (2.6)

\[ \vec{J} = \sigma \vec{E} \]  (2.7)

where \( \mu \) is the relative magnetic permeability, \( \varepsilon \) the relative dielectric function and \( \sigma \) the conductivity. By inserting (2.6) and (2.7) into (2.3), we obtain:

\[ \nabla \times \vec{H} = -i\omega \left( i\frac{\sigma}{\varepsilon_0} + \varepsilon \right) \varepsilon_0 \vec{E} = -i\omega \varepsilon \varepsilon_0 \vec{E} \]  (2.8)

where \( \varepsilon \) now is defined as an effective value, containing both dielectric and conduction effects. In most cases the contribution of conduction will however be small and \( \varepsilon \approx \varepsilon \). If the displacement field \( \vec{D} \) is not able to follow the oscillations in the electric field \( \vec{E} \) as described by equation (2.6), damping of
the oscillation will occur. This can be described mathematically by introducing an imaginary part in $\varepsilon$:

$$\varepsilon = \varepsilon_1 + i\varepsilon_2$$  \hspace{1cm} (2.9)

Similarly, the concept of refractive index $n$ can be expanded to include absorption by including an imaginary part in the form of the extinction coefficient $k$. A capital $N$ is used for this complex form:

$$N = n + ik$$  \hspace{1cm} (2.10)

The *Fresnel equations* describe the reflection and transmission of a plane electromagnetic wave incident at an angle $\phi_0$ on a planar interface between two materials with complex refractive indices $N_0$ and $N_1$,

$$r_s = \frac{E_{rs}}{E_{is}} = \frac{N_0 \cos \phi_0 - N_1 \cos \phi_1}{N_0 \cos \phi_0 + N_1 \cos \phi_1}$$  \hspace{1cm} (2.11)

$$t_s = \frac{E_{ts}}{E_{is}} = \frac{2N_0 \cos \phi_0}{N_0 \cos \phi_0 + N_1 \cos \phi_1}$$  \hspace{1cm} (2.12)

$$r_p = \frac{E_{rp}}{E_{ip}} = \frac{N_1 \cos \phi_0 - N_0 \cos \phi_1}{N_1 \cos \phi_0 + N_0 \cos \phi_1}$$  \hspace{1cm} (2.13)

$$t_p = \frac{E_{tp}}{E_{ip}} = \frac{2N_0 \cos \phi_0}{N_1 \cos \phi_0 + N_0 \cos \phi_1}$$  \hspace{1cm} (2.14)

where $r_s$, $r_p$ and $t_s$, $t_p$ are the Fresnel reflection and transmission coefficients, respectively, $E$ is the magnitude of the electric field and $\phi_1$ is the angle of refraction. $\phi_0$, $\phi_1$, $N_0$ and $N_1$ are also related through Snell’s law of refraction, $N_0 \sin \phi_0 = N_1 \sin \phi_1$.

The Fresnel equations are split up in reflection and transmission coefficients for the s- and p-polarized components of the light. The p- and s-coordinates are defined relative to the plane of incidence, which is the plane containing the incident, refracted and reflected light beams. For the s-polarized component, the electric field is normal to the plane of incidence (figure 1a) and for the p-polarized component, the electric field is parallel to the plane of incidence (figure 1b). As any incident wave can be written as a superposition of these two components, these equations are sufficient for all possible polarization states.
2.1.2 Reflection from layered structures

The above described theory only holds for a so-called two-phase system (figure 2a), where the interaction takes place at the interface of two materials with different indices of refraction. For layered structures, all the involved interfaces need to be taken into account. In a three-phase system (figure 2b), this means summing up light reflected at interface 01 and light transmitted at interface 01, reflected at interface 12 and transmitted at interface 10 and so on for higher order reflections. An effective reflection coefficient $R$ can then be written as a function of the Fresnel coefficients for the different interfaces:

$$
\begin{align*}
R &= \frac{E_{ip}}{E_{is}}
\end{align*}
$$

Figure 1: The (a) s-component and (b) p-component of polarized light incident on a planar interface.

Figure 2: Reflection on a (a) two-phase system and a (b) three-phase system.
where the subscripts denote the materials on either side of the interface. The exponential term describes the phase shift of the wave inside the layer, with the phase thickness $\beta$ given by:

$$\beta = \frac{2\pi d}{\lambda} N_1 \cos \varphi_1$$  \hspace{1cm} (2.16)

with $d$ the thickness and $N_1$ the refractive index of the layer, $\lambda$ the wavelength of the light and $\varphi_1$ the angle of refraction inside the layer. The sum in equation (2.15), with all the higher order reflections included, forms a geometric series and can be rewritten as:

$$R = \frac{r_{01} + r_{12} e^{i2\beta}}{1 + r_{01} r_{12} e^{i2\beta}}$$ \hspace{1cm} (2.17)

For multilayer structures, expressions for the effective reflection coefficient can be derived in a similar way, but the expressions become very long and inconvenient. A matrix formalism can be used to solve this problem. This formalism is called the Abelès formalism [2] or scattering matrix method [3].

A matrix equation $E(z_1) = S E(z_2)$ is defined as follows:

$$\begin{bmatrix} E^+(z_1) \\ E^-(z_1) \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} E^+(z_2) \\ E^-(z_2) \end{bmatrix}$$ \hspace{1cm} (2.18)

where $E^+$ and $E^-$ are the complex field vectors of the forward and backwards traveling waves, respectively, for planes at positions $z_1$ and $z_2$. If the two planes are chosen in the ambient and the substrate, the scattering matrix $S$ contains contributions from all the interfaces and layers and thus describes the whole system. From the scattering matrix, effective reflection coefficients $R_p$ and $R_s$, can be calculated, so that (for isotropic media):

$$\begin{bmatrix} E_{rp} \\ E_{rs} \end{bmatrix} = \begin{bmatrix} R_p & 0 \\ 0 & R_s \end{bmatrix} \begin{bmatrix} E_{ip} \\ E_{is} \end{bmatrix}$$ \hspace{1cm} (2.19)

This is the Jones matrix formalism, which is used for describing ellipsometric systems (see section 2.2). Any (non-depolarizing) polarization altering component can be described by a Jones matrix. A complete system can then be described by multiplying the Jones matrices of the individual components. For anisotropic systems, the off-diagonal elements of the Jones matrix may become nonzero and the analysis becomes more complicated.
2.1.3 Effective medium approximation

When doing optical analysis, one frequently encounters mixtures of materials with known optical properties for the constituents. If the local variations of the optical properties are of a much smaller scale than the wavelength of the light, the mixture can be modeled as a continuum. The optical properties of the mixture can be calculated from the optical properties of the constituents. For this purpose, effective medium approximation (EMA) methods have been developed. Several different EMA models exist, optimized for different microstructures. Only the Bruggeman EMA model is treated here, since it has been proven fairly successful for the applications described in this work.

The Bruggeman EMA assumes spherical unit cells for all constituents in the mixture. For $n$ materials with volume fraction $f_i$, and dielectric function $\varepsilon_i$, the effective dielectric function $\varepsilon_{\text{eff}}$ can then be defined using the following equation:

$$\sum_{i=1}^{n} f_i \frac{\varepsilon_i - \varepsilon_{\text{eff}}}{\varepsilon_i + 2 \varepsilon_{\text{eff}}} = 0 \quad (2.20)$$

and condition

$$\sum_{i=1}^{n} f_i = 1 \quad (2.21)$$

This model is frequently used to describe both surface roughness [4] and porosity [5]. In both cases the material is described as a mixture of the substrate material and void.

2.2 Ellipsometry

Ellipsometry [3] is an optical technique for determining the optical properties and microstructure of surfaces and thin films. It is based on measuring the polarization change that occurs when light is reflected by or transmitted through a surface or film. Reflection ellipsometry will be considered in the remainder of this text. The technique has two main advantages. First, it is a non-destructive measurement ‘from a distance’, which makes it very suitable for in-situ real-time measurements. Second, because the measured variable is polarization change, it is essentially insensitive to drift in the intensity of the light source and the spatial resolution for determining film thickness is not limited by the diffraction limit, enabling changes in layer thickness in the order of pm to be detectable in principle.
2.2.1 Principles

Ellipsometry measures the change of polarization of light upon reflection of a surface. The polarization state of the incident wave can be defined as the ratio of the complex electric field vectors in the p- and s-direction:

\[ \chi_i = \frac{E_{ip}}{E_{is}} \]  

(2.22)

and the polarization state of the reflected wave:

\[ \chi_r = \frac{E_{rp}}{E_{rs}} \]  

(2.23)

The polarization change upon reflection can then be defined as the ratio of these states:

\[ \rho = \frac{\chi_r}{\chi_i} \]  

(2.24)

If the sample is isotropic, equation (2.19) gives \( R_p = \frac{E_{rp}}{E_{ip}} \) and \( R_s = \frac{E_{rs}}{E_{is}} \) and (2.24) can be rewritten as:

\[ \rho = \frac{R_p}{R_s} \]  

(2.25)

This complex reflectance ratio is determined by standard ellipsometry, and is usually expressed as:

\[ \rho = \tan \Psi e^{i\Delta} \]  

(2.26)

With \( R_p = |R_p| e^{i\delta_{rp}} \) and \( R_s = |R_s| e^{i\delta_{rs}} \), it follows that

\[ \tan \Psi = \frac{|R_p|}{|R_s|} \] and \( \Delta = \delta_{rp} - \delta_{rs} \)  

(2.27)

Thus \( \tan \Psi \) and \( \Delta \) are the differential changes upon reflection in amplitude and phase, respectively, of the components of the electrical field vector parallel and perpendicular to the plane of incidence. \( \Psi \) and \( \Delta \) are the variables that are obtained from an ellipsometry measurement. Depending on the amount of information needed, they can be obtained as a function of wavelength, angle of incidence, time, or a combination of these.
2.2.2 Measurement

To conduct an ellipsometric measurement, one first needs an incident beam with known polarization, which is reflected on the sample, after which the change in polarization needs to be determined. A very common setup is the PCSA system (see figure 3), which stands for Polarizer Compensator Sample Analyzer. This is the order of the components between the light source and the detector. The light source is usually a laser or some other monochromatic light source. The polarizer and analyzer are both linear polarization filters and the compensator is a quarter wave plate, with which an arbitrary elliptical polarization can be obtained by inducing a phase shift between the p- and s-components of the polarization vector. When the azimuths of the polarizer and analyzer are set in such a way that no light hits the detector (nulling), $\Psi$ and $\Delta$ can be calculated from these angles.

For spectroscopic ellipsometry, nulling the system for every wavelength would become very tedious and time consuming. Therefore a Rotating Analyzer Ellipsometer (RAE) is used in this case. The analyzer in this system rotates at a constant speed, while the polarizer is kept in a fixed position. The linearly polarized incident light (the compensator is often omitted in this system) will generally be converted to elliptically polarized light, which gives a sinusoidal signal on the detector due to the rotating analyzer. By a Fourier analysis of the signal, the ellipsometric angles $\Psi$ and $\Delta$ can then be determined.

2.2.3 Analysis

Generally, the desired properties of the measured sample cannot be directly calculated from the measured $\Psi$ and $\Delta$. For this reason, ellipsometry is called an indirect technique. For any sample with known properties, however, the outcome of an ellipsometry measurement can be predicted using the matrix formalisms mentioned in section 2.1.2: the reflection coefficients of the

---

**Figure 3: PCSA ellipsometry setup.**
sample can be calculated using the scattering matrix method and the Jones matrix formalism can then be used to model the ellipsometric system. The calculated result can then be compared to the measured data and if needed adjusted to better fit the measured data.

The comparison and model tuning is performed as an iterative fitting process by a computer. In short the procedure is as follows. First, a measurement is performed to collect information about the sample in the form of ellipsometric angles. In principle the more information the better, since this gives a better basis for the mathematical fit. More information can be obtained by measuring at multiple wavelengths or multiple angles of incidence or both (variable angle spectroscopic ellipsometry). Second, a model is built up using what is known about the measured sample to define a layered structure with layer thicknesses and optical properties as close to the real values as possible. In case of materials with known optical properties, database values from earlier measurements can be used in the model. Third, some of the parameters (film thickness, optical properties) in the model are defined as variables, to be changed in the fitting process. Fourth, the mean square error (MSE) value is calculated, which is used as a measure for the quality of the fit. Fifth, the parameters defined as variables are changed in order to decrease the MSE value. Step four and five are repeated until a minimum value of the MSE is reached.

### 2.2.4 Structure and analysis of porous silicon

Porous silicon (see also appendix A) was discovered in the mid fifties [6]. Since then it has had an undying attention in scientific literature. Much work has been done to better understand this complex material. The attention became even greater after reports of room-temperature photoluminescence [7] and electroluminescence [8]. Exploitation of the material as a gas sensor, as described in this work, is only one of many applications currently under investigation. Both its versatility and its relative ease of fabrication make it applicable in many different fields. One of these fields, gas sensing (see also [9]), is explored in paper I.

A scanning electron microscopy (SEM) picture of a porous silicon sample is shown in figure 4. The dark spots on the picture are the pores, which are in the order of about 5-10 nm in size. The properties of the porous material, such as layer thickness, porosity, pore size and shape, etc., can vary largely depending on etching conditions such as HF concentration, doping concentration, crystal orientation, current density, etc. [10]

For the experiments described in this work, pore sizes of 10 nm or less are used. Since these are small compared to the wavelength of the visible light used in the ellipsometry measurements, the material can be treated as a homogeneous medium using an effective medium approximation (EMA, see section 2.1.3). Designing a good model for a material as complex as porous silicon is
however far from trivial. By using a multilayer model [5] with several EMA layers with varying porosity to mimic a porosity gradient normal to the surface, a reasonable fit can be obtained. For gas sensing purposes, however, extensive modeling is not necessary, since not the absolute properties of the sample are important, but the relative change which arises when gas adsorbs to the surface.

2.3 Fluorescence

When molecules absorb ultraviolet or visible light, they are elevated to an excited electronic state. Generally, this excess energy will be dissipated as heat. Under certain conditions, however, some of the excess energy can be reemitted as light of a different wavelength. This process is called photoluminescence [11]: luminescence for the general effect of molecules emitting light in a deexcitation process, photo- because the excitation is caused by photons (as opposed to, for example, chemiluminescence). Fluorescence, which plays an important role in this work, is a form of photoluminescence. For better understanding, a more detailed look at the process of excitation and emission is necessary.

Figure 4: SEM image of a porous silicon surface.
2.3.1 Excitation and emission

What happens to the energy after absorption, can be depicted in a so-called Jablonski diagram (figure 5). To know what kind of emission is seen, one needs to look at the molecular multiplicity $M$:

$$M = 2S + 1$$

(2.28)

where $S$ is the spin quantum number of the molecule, defined as the sum of the net spin of all electrons in the molecule. For most organic molecules, $S=0$, since the number of electrons is even. The multiplicity is then equal to 1 and the state is referred to as a singlet state. When the molecule is in an excited state, it is possible for one electron to change its spin. Then $S = \frac{1}{2} + \frac{1}{2} = 1$ and $M = 2 \cdot 1 + 1 = 3$. This is called a triplet state. The states are numbered by level of excitation: $S_0$, $S_1$, $S_2$, etc. for the singlet states and $T_1$, $T_2$, etc for the triplet states (there is no $T_0$, since in the ground level all spins are paired).

When a photon is absorbed by the molecule, it is excited to a higher singlet state (see figure 5). Let us assume the molecule is excited to $S_2$. It will immediately dissipate excess vibrational energy in the form of heat by collision with surrounding molecules. This process is called vibrational relaxation (VR). At the same time, a transition can occur from a low vibrational level in $S_2$ to a higher vibrational level with the same energy in $S_1$. This is called internal conversion (IC). After this, the molecule can further relax to the lowest vibrational level in $S_1$. These processes occur on a short time scale ($\sim 10^{-12}$ sec). Further vibrational relaxation to the $S_0$ level is however usually relatively slow. This enables relaxation by emission of a photon. This process, deexcitation from $S_1$ to $S_0$ by emission of a photon is called fluorescence. If a further transition occurs from $S_1$ to $T_1$ by a process called inter system crossing (ISC), the relaxation from $T_1$ to $S_0$ by photon emission is called phosphorescence.

Figure 5: Jablonski diagram.
2.3.2 Fluorescence in practice

There is a wide range of applications for fluorescence in biomedical applications. Many bioassays are based on attaching a fluorescent marker to a target molecule, for example an antibody or a DNA strand. Measuring the fluorescent emission during or after a reaction involving the marked molecule enables quantitative analysis of the reaction.

Quenching

Some practical considerations should be noted when dealing with fluorescence spectroscopy. It is important to know that fluorescence can be inhibited by a deactivation process known as quenching. Several mechanisms are known to cause quenching [12], but all involve radiationless deexcitation by interaction with other (quencher) molecules. This can be used to one’s advantage to turn fluorescence on or off at will, but should of course be noted when designing experiments, to make sure no accidental unwanted quenching occurs.

Polarization

When polarized light is used to excite fluorescent molecules, absorption will be most likely to occur for molecules which have their absorption transition vectors aligned parallel to the polarization of the exciting light. Depending on the mobility of the molecules and the lifetime of the excited state, the polarization of the emitted light may vary. The degree of polarization of the emitted light can be defined as

\[ P = \frac{I_{f||} - I_{f\perp}}{I_{f||} + I_{f\perp}} \]  

(2.29)

Where \( I_{f||} \) and \( I_{f\perp} \) are components of the polarization of the emitted light parallel and perpendicular, respectively, to the polarization axis of the exciting light. This value can vary from -0.33 to +0.5 [12]. The degree of polarization will be higher for higher molecular weight of the fluorophore, higher solvent viscosity and shorter excited state lifetime. This effect can be utilized for a fluorescent polarization (FP) measurement, which gives information about molecular orientation and mobility. This can be of value in studies of interaction of organic molecules, for example. It is also useful to filter out transmitted computer screen light in the CSPT fluorescence setup (see paper III), by using crossed polarizers.
3.1 Introduction

The computer screen photo-assisted technique, CSPT in short, is central in this thesis. It uses a computer screen as light source for optical measurements and, in most cases, a web camera for detection. The great advantage of doing this is that regular personal computers, which are available almost everywhere, can be used for measurements which normally require expensive laboratory equipment or dedicated readers. Though the latter may be cheap, they are very specialized. The idea behind the CSPT concept is that it is both cheap (assuming the computer is already available) and versatile. By using the inherent possibilities of the computer screen and web camera, the CSPT system can be optimized for the desired application. The web camera, for example, can do imaging as well as color analysis, enabling simultaneous measurement of multiple color samples. The screen, as a programmable light source, can provide color and intensity modulation as well as positioning without moving parts. If an LCD screen is used, the linearly polarized light from the screen can be used for ellipsometric measurements.

3.2 Challenges

Though the physics behind the CSPT measurements is essentially the same as in the traditional measurements it is based on, there are some aspects one needs to be aware of. Most important is that, in CSPT, both the light source (the computer screen) and the detector (the web camera) are not based on monochromatic light, but on reproducing color adapted to human vision. The cones [13] in the retina of the human eye are responsible for color vision. They are divided into three subtypes, sensitive to short, medium and long wavelengths in the visible spectrum (~350-700 nm), roughly corresponding to blue, green and red, respectively. Because the only information available to the brain is the relative intensity in these spectral bands, the eye cannot do spectroscopic measurements. This is an advantage for color reproduction, since not the complete spectrum needs to be reconstructed. In most cases, the spectral distribution of a reconstructed color will be quite different, but since the relative intensity in the three spectral bands of the cones is the same, the reconstructed color is perceived to be the same as the original. Computer screens, cameras and other ways to reproduce color, like printing, are based on this.
principle [14] and it is important to understand the basics of how these devices function.

### 3.3 Computer screens

The most important output peripheral of a computer is certainly the screen. Nearly everything communicated to the user is displayed as visual information. New improvements are constantly emerging to make the screens more user friendly, with higher resolutions and refresh rates, more viewing comfort, etc.

#### 3.3.1 CRT

A cathode ray tube (figure 6) is based on an electron beam which is scanned over a surface covered with phosphors, which are excited by the electrons and in turn emit light. Its core is an evacuated ‘bottle’ with an electron gun in the narrow end. In color screens there are three separate electron beams, one for each color. These three beams are focused onto three phosphors with different colors within one picture element (pixel). These three phosphors are so closely spaced that the eye cannot distinguish them and are seen as one average color (color fusion).

In the electron guns, electrons are released from the cathode by heating and subsequently focused and accelerated toward the anode. The deflection yoke creates a modulated magnetic field, directing the electron beam toward the desired spot on the screen. The electron beam is scanned from left to right (as seen from the front) and from top to bottom, lighting up the phosphor dots in sequence as it goes. The refresh rate (frequency with which the whole screen is scanned, also called vertical scanning frequency, VSF) is dependent on the resolution (number of pixels per unit area), and the horizontal scanning frequency (HSF). For modern CRT computer screens, the refresh rate is usually between 75 and 100 Hz.

*Figure 6: Schematic view of a CRT screen.*
Liquid Crystal Displays (LCD) do not emit light in the pixels themselves, but instead control the transmission of a backlight separately for each pixel. The backlight emits white light; color is produced by using color filters for the separate color elements in each pixel. Colors are again produced by color fusion. The liquid crystals in the screen consist of rod-like molecules, which are aligned to a finely grooved surface on both sides of the screen (see figure 7). The grooves are aligned perpendicularly on either side, causing the molecules to twist their alignment from one direction to the other between the two boundaries. Polarized light passing these twisted molecules will twist its polarization direction according to the orientation of the molecules. Thus, with a polarization filter on each side, the light will pass when the polarizers are crossed, since the polarization is rotated 90 degrees by the molecules. When a voltage is applied between the two boundaries, the molecules will prefer alignment with the potential, giving them a vertical alignment (figure 7, Right). Now light passes between the polarization filters without changing its polarization, causing it to be blocked by the second polarization filter. Thus, the transmission of light can be controlled.

LCD screens usually operate at a lower refresh rate. Since, unlike in CRT screens, the light intensity of the pixels does not decay shortly after being set, it can operate flicker free even at low frequencies. Long response time of the liquid crystals used to be a problem. However, with the current state of the art this does not pose a practical problem anymore for most applications.
3.4 CCD

For recording light, any technique involving light being absorbed and leading to a detectable physical effect can in principle be used. For traditional photography, light-sensitive chemicals constitute this effect. In digital recording, however, a chemical conversion does not suffice, since an electric signal is needed. Charged coupled devices (CCD’s) are the most common choice in this case.

3.4.1 Physical principle

A CCD [15] photodetector is based on the photoelectric effect [16]. It consists of an array of metal-insulator-semiconductor (MIS) capacitors, usually of the form metal-oxide-silicon (MOS). When the silicon is hit by photons, it ‘releases’ electrons (the electrons are excited to the conduction band). These electrons are collected in the MOS capacitors and after a certain exposure time, the charge buildup is measured. Since the number of released electrons is proportional to the intensity of the incident light, this measurement corresponds to an intensity measurement. Electrons can also be released by thermal effects, creating the so-called dark current. This limits the exposure time, because the signal is masked by the thermal noise for long exposures. For low intensities, the amplifier gain can be raised to get a stronger signal.

![Figure 8: Readout of a CCD chip using a Bayer pattern to create a color image.](image)
3.4.2 Readout

Each MOS capacitor functions as a small well in which the released electrons are trapped. During the recording phase the wells are isolated from each other, preventing electrons from moving between wells. In the readout phase however, applying an appropriate voltage to a cell will ‘deepen’ its potential well, causing electrons from an adjacent cell to be transferred into it. This coupling between the cells gives the CCD its name. This phenomenon is used to sequentially read all the pixels by moving them in an ordered fashion (see figure 8). The charges are moved in lines toward a readout register, where the cells are moved one by one to an amplifier. The amplifier converts the charge into a voltage, which is in turn converted by an AD-converter, enabling it to be processed by a computer. Moving the charges is achieved by applying a controlled series of clock pulses. For a detailed description, see [15].

3.4.3 Color

Though CCD image sensors have a certain spectral response curve, they are essentially insensitive to color. Therefore, filters need to be applied to be able to detect colors. In single chip devices, such as web cameras or conventional digital cameras, filters are applied to each cell on the chip separately, creating an array of red, green and blue cells (e.g. a Bayer pattern, see figure 8). Thus, two colors are never recorded at exactly the same position. For closely spaced cells, this poses no problem in practice, since color fusion will ensure that this is not detectable to the human eye. Another technique, which can provide better quality (resolution), but is much more costly, is to use a separate detector for each color, using a beam splitter to separate the incoming light. Triplets of color values are usually combined as individual picture elements (pixels), each pixel containing three values varying from 0-255, giving the intensity of red, green and blue light for that pixel.

3.5 Applications of CSPT

In principle almost any measurement principle based on interaction of light with a sample can be adapted for CSPT. One of the early applications, which did not use a web camera for detection, was based on a scanning light pulse technique (SLPT) [17], [18]. In this technique, a large-area field-effect device is used, with different catalytic metals forming the gate. Scanning the surface with a pulsed light beam generates a photocapacitive current. This current is dependent on the interaction between gases and the different metals on the surface and thus a fingerprint of the gases that are present can be formed by scanning over the whole surface. Traditionally, a scanning laser pulse is used, but it has been demonstrated that distinctive chemical images can be formed by instead using a computer screen as light source and scanning the illumina-
tion over an area on the screen [19] or illuminating the whole sensor area simultaneously and scanning bias voltage and illumination color [20].

Many of the applications of CSPT are based on color analysis using a web camera together with the computer screen. Though traditional spectroscopy is not possible using this system, spectral reconstruction combining trichromatic cameras with absorption filters or different light sources has been demonstrated previously [21]. The aim of CSPT however is not to achieve full spectral reconstruction but to gather enough data to produce a spectral fingerprint representative of the analyzed substance. Many chemical and biochemical assays make use of visible absorption measurements (see for example [22]). CSPT can be used as an affordable evaluating platform for such assays by measuring the transmitted light for a range of colors on the screen that enable the generation of distinctive spectral fingerprints [23]. The imaging capability of the web camera can be exploited to measure several samples simultaneously, for example in a microtiterplate [24]. In similar measurements, fluorescent substances can also be classified [25]. Further work on fluorescence measurements is described in this thesis, demonstrating methods to separate the emitted from the transmitted light. Colorimetric testing can also be used for reflectance measurements [26]. This can be readily applied for home testing purposes, by using existing urine test strips [27]. When polarizers are used with the reflectance measurements, ellipsometry-based analysis is possible, as described in this thesis.

3.6 CSPT fluorescence measurements

3.6.1 Cuvette setup

Fluorescent substances can be detected in a CSPT setup in much the same way as non-fluorescent colored substances, as demonstrated in [25]. However, since the intensity of the transmitted light is much higher than that of the emitted light, especially for low concentrations, this does not benefit much from the fluorescent emission. In a normal transmission setup, the limiting factor for the sensitivity is the dynamic range of the camera. If the emitted light can be filtered out completely so that only the emitted light is measured, the detection limit depends instead on the sensitivity of the camera. This can be boosted by increasing the shutter time and amplification and much higher sensitivity may be possible. One way to keep the transmitted light from reaching the detector is to measure from the side as demonstrated in paper II. Though some transmitted light still reaches the detector in this setup, an improvement in sensitivity is observed as expected.
3.6.2 Micro well setup

To decrease the analyte volume needed and to enable measurement of multiple samples simultaneously, an array of micro wells was designed for the CSPT fluorescence measurements (paper III). When measuring fluorescent substances in an array of micro wells, measurement from the side is no longer possible. Partly because the dimensions are too small - the wells are about 0.5 mm deep - and partly because only the wells on the edge will be visible from the side. Therefore, a new method for eliminating the transmitted light had to be found. In this setup, the sample was placed between two crossed polarizers to achieve extinction of the transmitted light. A disadvantage of this is, that more than half of the computer screen light (in case of a CRT screen - for an LCD screen, the already polarized screen light can be used to ones advantage) is absorbed by the polarizer before it can reach the sample. This implies less light will be absorbed by the sample and thus less light is emitted. However, since the crossed polarizers are very effective for extinguishing the transmitted light, this can be compensated for by increasing the web camera sensitivity to its maximum. Of course care needs to be taken that the polarization of the light is not altered on its path between the polarizers. Therefore, any reflecting or focusing optics have to be placed outside the polarizers. Plastics often display tension-induced birefringence and should therefore not be in the light path between the polarizers. This is the reason why a light mask is applied to shield the light at places where the SU-8 plastic is applied (see appendix A), which forms the micro wells.

3.7 CSPT ellipsometry

With polarizers being used in the fluorescence setup, the step toward ellipsometry measurements was not very big. Some ideas about testing ellipsometry in a CSPT setup already existed, but so far they had not been implemented. In the fluorescence setup, some contaminations that were otherwise hardly visible showed up very clearly. To explore this effect further, an ellipsometry setup was designed. The first setup was built with an angle of incidence of 70º and using the polarization direction of the LCD screen, which was at an azimuth of 45º. Note that the angle of incidence is dependent on the position on the sample, so the actual angle of incidence is distributed around 70º.

The setup was later improved according to the optimization presented in section 4.1, with a polarization azimuth of 0º and angle of incidence centered at approximately 78º. This gave much higher sensitivity, though also a stronger dependence on the angle of incidence. Because of this, measurements are only possible within a narrow region unless collimating optics are used.
4.1 CSPT ellipsometry optimization

The ellipsometry setup presented in paper IV produced good results. However, to be able to measure biomolecules, the setup had to be optimized to give maximum reflected intensity for small layer thicknesses. The following Matlab® script simulates the measurements and calculates the reflectance (or reflected intensity if the incident intensity is unity) as a function of the angle of incidence:

```matlab
lambda=445; %wavelength, blue light
Si_N=4.73+0.083*i; %silicon refractive index
SiO2_N=1.47; %silicon dioxide refractive index
d=5; %layer thickness 5 nm
AngInc=70:.01:85; %angle of incidence
for n=1:length(AngInc)
    %Calculate angles using Snell’s law
    Phi0=AngInc(n)*pi/180; %degrees converted to radians
    Phi1=asin(sin(Phi0)/SiO2_N);
    Phi2=asin(SiO2_N*sin(Phi1)/Si_N);
    Phix=asin(sin(Phi0)/Si_N); %No oxide nulling
    %Fresnel reflection coefficients without silicon dioxide
    r02p=(Si_N*cos(Phi0)-cos(Phix))/(Si_N*cos(Phi0)+cos(Phix));
    r02s=(cos(Phi0)-Si_N*cos(Phix))/(cos(Phi0)+Si_N*cos(Phix));
    A=0:.001:pi;
    null_refl=(abs(r02p*cos(A)+r02s*sin(A))).^2; %for P=45 deg
    null_refl=[null_refl(1:length(AngInc)) ones(1,1)]; %nulling
    [minimum,index]=min(null_refl); %find minimum
    A=A(index); %analyzer is set to azimuth with lowest intensity
    %Calculate Fresnel reflection coefficients for both interfaces
    r01p=(SiO2_N*cos(Phi0)-cos(Phi1))/(SiO2_N*cos(Phi0)+cos(Phi1));
    r01s=(cos(Phi0)-SiO2_N*cos(Phi1))/(cos(Phi0)+SiO2_N*cos(Phi1));
    r12p=(Si_N*cos(Phi1)-SiO2_N*cos(Phi2)) ./ (Si_N*cos(Phi1)+SiO2_N*cos(Phi2));
    r12s=(SiO2_N*cos(Phi1)-Si_N*cos(Phi2)) ./ (SiO2_N*cos(Phi1)+Si_N*cos(Phi2));
    %Calculate effective reflection coefficients
    Beta=(2*pi/lambda)*SiO2_N*cos(Phi1)*d; %phase thickness
    Rp=(r01p+r12p*exp(i*2*Beta))./(1+r01p*r12p*exp(i*2*Beta));
    Rs=(r01s+r12s*exp(i*2*Beta))./(1+r01s*r12s*exp(i*2*Beta));
    reflectance(n)=(abs(Rp*cos(A)+Rs*sin(A))).^2; %P at 45 degrees
end
plot(AngInc,reflectance)
xlabel('Angle of incidence (deg)')
ylabel('Intensity change (5 nm)')

[m,index]=max(reflectance); %calculate optimum angle of incidence
Optimum=AngInc(index)
```

Optimum = 23
The script assumes a polarizer azimuth of 45° and angles of incidence varying from 70° to 85°. First the reflectance is calculated with no silicon dioxide present as a function of the analyzer azimuth, which is set to the value giving the lowest intensity (nulling). Then the reflectance with a layer of 5 nm silicon dioxide is calculated and plotted as a function of the angle of incidence. Finally, the angle of incidence for which the reflectance reaches its maximum is calculated, which is the optimal angle of incidence.

The graph produced by the script is shown in figure 9. The calculated optimum angle is 79.0°. As seen in the figure, this will give almost 50% improvement compared to a setup with an angle of incidence of 70°. Note that this is for a polarizer azimuth of 45°. The Brewster angle of silicon for the selected wavelength is approximately 78°, which is close to the calculated optimum. At the Brewster angle, no p-polarized light is reflected from bulk silicon and in the nulling condition the analyzer will be parallel to the plane of incidence. Thus any change in \( R_s \) will not be detected and only p-polarized light contributes to the measurement. Therefore, the polarizer can be set parallel to the plane of incidence, which means the intensity of the p-polarized light is twice as high. This gives an additional 100% increase in sensitivity compared to the setup with \( P=45° \). These optimized conditions are used in paper V for protein measurements. Note that this is technically not ellipsometry, since only \( R_p \) is measured and not the reflectance ratio \( R_p/R_s \).

### 4.2 CSPT ellipsometry on thicker layers

When light is reflected on a sample with a transparent film which has a thickness in the order of the wavelength of the light or larger, interference effects will occur. More precisely, constructive interference will occur if the path length of the light inside the film is an integer number of wavelengths [28]:

\[
m\lambda = 2nd \cos \phi \tag{4.1}
\]

with \( m \) a positive integer, \( n \) the refractive index and \( d \) the thickness of the layer and \( \phi \) the angle of refraction. Destructive interference occurs if

\[
\left( m + \frac{1}{2} \right)\lambda = 2nd \cos \phi \tag{4.2}
\]
Note that equations (4.1) and (4.2) are valid for a thin film in air. If the film is deposited on a higher index material (e.g. SiO$_2$ layer on an Si substrate), the interference conditions will be reversed. The interference makes the reflection strongly wavelength dependent, which in turn leads to color effects. To test this interference effect in the CSPT ellipsometry setup, silicon dioxide steps were etched (see section A.3) with thicknesses up to a few hundred nm. A typical image recorded from such a sample is shown in figure 10.

Measurements for thicker layers were also compared to theory using the model described in paper IV. Measurement data and model fit are shown in figure 11. As seen in this figure, even for thicker layers the data corresponds to the model quite well. Though biomolecules will not form layers in this thickness range, there may still be interesting applications. For example using thick layers which change thickness and/or refractive index by absorbing an analyte. Instead of intensity, color change would then be a measure.

Figure 10: Sample with thicker layers, leading to interference color effects.

Figure 11: CSPT ellipsometry measurement and model for layer thicknesses up to ~200 nm.
Chapter 5

Prospects

The measurements described in this thesis are all still very much in a development status. More experimental work and development will be needed before they are ready for the commercial market. Suggestions for future work are summarized in this chapter.

5.1 Porous silicon gas sensing

The work presented in this thesis on gas sensing using porous silicon and ellipsometry (paper I) was only part of a larger project. In this thesis, improvement of the porous silicon as sensing layer by depositing polymers was presented. Both on the sensing system itself and the improvement by modification of the layer, much development is still possible.

- A sensor based on this principle was presented in [29]. This sensor can be developed further and several sensors can be combined to form a sensor array as suggested.

- Influence of different polymers on the sensitivity can be investigated. Different polymers may also influence the sensitivity differently for different analyte gases, improving the selectivity of the sensors.

- Modification using other materials can also be tested. Copper modification was already presented in [30].

5.2 CSPT fluorescence

- The micro well structure fabricated using photolithography on SU-8 (see appendix A) showed detachment and cracking problems due to tension in the SU-8 layer. This may be solved by creating the walls of the wells as separate structures instead of one continuous layer. A lithography mask has already been developed for testing this, see figure 12.

- Depositing fluorescent solutions into the wells was hindered by surface tension of the drops. Surface modification and/or changing the shapes of the wells may facilitate deposition. Several different shapes are tested in the mask in figure 12 for this purpose.
Eventually, a micro well structure with embedded flow system will be needed.

CSPT fluorescence measurements also need to be tested with real applications, like ELISA tests or other biochemical assays.

5.3 CSPT ellipsometry

- Standardized samples with robust calibration need to be developed and tested for biosensing applications.
- Tests may be done on sensing based on color change of thicker layers, for example porous silicon.
- The system may be adapted for total internal reflection ellipsometry [31] or SPR [32] measurements.
- To make measurements on other (e.g. metal) substrates possible, a setup including a compensator (wave retarder) needs to be developed.

Figure 12: Lithography mask for micro wells. Different shapes of the wells for assisting deposition.
References


References


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Appendix A

Sample preparation

A.1 Porous silicon

The most common fabrication method for porous silicon is electrochemical etching or anodization. This method is fast and simple and provides a high level of control over the etching process. A schematic overview of the etching setup is shown in Fig. A.1. The silicon sample is submerged in a solution containing hydrofluoric acid (HF), ethanol and water. The ethanol is used because it is assumed to facilitate the removal of hydrogen, which is a byproduct of the etching process. This should result in more uniform porous layers. A galvanostat is used to maintain a constant current during the etching. A constant voltage would not be advantageous, since the resistivity of the sample changes during the etching process, because porous silicon has a higher resistivity than crystalline silicon. Silicon is connected to the positive pole of the galvanostat (hence the name anodization) and a gold wire is used as counter electrode.

The porous silicon samples presented in this thesis are rectangular pieces of 2.5x2 cm cut from a silicon wafer with crystal orientation <111>, of which a 2x2 cm area is submerged in the etching solution. Etching is performed in a mixture of 15% HF, 41% ethanol and 44% water with a current density of 30 mA/cm² for 20 seconds.

A.2 Micro array for fluorescence measurements

The micro array used for fluorescence measurements in paper III is created on a microscope glass slide. The fabrication comprises several steps. First, the glass slides are submerged in a solution containing 5 parts H₂O, 1 part H₂O₂ and 1 part NH₃ and heated to 80 °C for 5 minutes to remove organic contaminants. After this cleaning step, the slides are placed in a vacuum chamber,
where approximately 100 nm of chromium (Cr) or aluminum (Al) is deposited by thermal evaporation. The slides are then stored at 100 °C for at least 12 hours to prevent the presence of moisture.

The well structure is created by photolithography using the photosensitive polymer SU-8 from MicroChem. This is an epoxy-based negative resist. Highly viscous SU-8 50 is used for creating thick layers. The following steps are taken to fabricate the wells:

- The sample is inserted in a spin-coater and SU-8 is deposited on it
- The spin speed is ramped to 500 rpm (acceleration ca. 85 rpm/s) and held at this speed for 5 seconds (spread cycle)
- The spin speed is further ramped to 1000 rpm (acceleration ca. 340 rpm/s) and held at this speed for 35 seconds (spin cycle)
- The sample is then put on a hot plate at 60 °C, which is ramped up to 95 °C in approximately 8.5 minutes and held at this temperature for 30 minutes (soft bake)
- The spinning and soft bake steps are repeated once to increase the thickness
- A mask with circles with a diameter of approximately 0.5 mm is placed over the sample and it is exposed to uv light for 2 minutes (amounting to 720 mJ/cm²)
- The sample is placed on a hot plate at 75 °C, which is ramped to 95 °C in approximately 5 minutes and held at this temperature for 30 minutes. During this step (post exposure bake) the exposed SU-8 is cross-linked
- The sample is then placed in developer for 30 minutes, which removes the unexposed SU-8
- Finally, the slides are placed in an etching solution which etches away the metal from the bottoms of the wells, thus finishing the light mask.

### A.3 Silicon dioxide steps

Steps of silicon dioxide (SiO₂) on silicon (Si) were used as a model system for the CSPT ellipsometry measurements presented in this thesis. To fabricate these, silicon wafers were first thermally oxidized (subjected to controlled oxygen flow at high temperature). Since SiO₂ is soluble in hydrofluoric acid (HF), diluted solutions of HF can be used for controlled etching. It was found that a 2% HF solution (1 part HF 40% and 19 parts H₂O) gives an etching rate
of approximately 20 nm/min and an 8% HF solution approximately 1 nm/s. Note that the etching rate decreases over time, which is probably a saturation effect. These concentrations were used for etching the thin layers (paper IV) and the thick layers (4.2), respectively. The wafers were cut in strips of approximately 1.5x8 cm and placed in a narrow container. HF solution was added in this container stepwise at fixed intervals, causing different exposure times to the solution at different positions on the sample, thus creating thickness steps.
Epilogue

About five years of research put together in less than a hundred pages. Is that really possible? I guess it depends... Certainly all important results are mentioned. That’s what a thesis is for after all. All the thought processes and trial and error experiments leading to these results are not mentioned. Most of them wouldn’t be very interesting anyway, although some may be quite educational: it’s never wrong to learn from someone else’s mistakes. But to get to the point: what really is missing are all the other experiences and people that made my stay in Linköping and work at university an overall very enjoyable experience. Since this is really not in place in a scientific thesis and it seems like it wouldn’t fit on a thousand pages, I will just try to keep it short here.

While finishing my master of applied physics program at Twente University in Enschede, the Netherlands, I really did not know where I would end up. When I received an invitation from Linköping to follow a PhD education there, I did not hesitate long. I had been to Linköping before as an exchange student for a few months and enjoyed my stay there very much, both the work in the Applied Optics group and life in general. The five postgraduate years were no different. For those years I have many people to thank.

The Applied Optics PhD students Alexander, Linda, Guoliang, Michał, Torun and Saby and of course the rest of the group for scientific and other times, countless lunch and coffee breaks and forming the core of the corridor.

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Now the time has come for new adventures!
Goodbye and thanks for all the fish (not just the fermented ones)!

Jimmy Bakker, April 2006