Correlating Photoconductivity with Photochromism in Oxygen-containing Rare-earth Metal Hydride Thin Films

Suraya Kazi
Abstract

**Correlating Photoconductivity with Photochromism in O-containing Rare-earth Metal Hydride Thin Films**

*Suraya Kazi*

Scientists have recently discovered simultaneous photoconductivity and photochromism (i.e., optical switching upon light exposure) of oxygen-containing rare-earth metal hydrides (REMHO). A deep understanding of these extraordinary optical and electrical properties can open the door to advanced technological uses such as smart windows. This thesis work is to establish a correlation between the photochromism of these materials with their photoconductive response and comprehend the underlying physics behind them. The samples were grown by reactive magnetron sputtering. The dynamics of the photochromic effect were observed by recording the time-resolved relative transmittance of the films during photodarkening and bleaching using a UV-vis spectrometer. The samples were characterized electrically by employing the two-point probe resistance measurement. The depth profiles of the concentration of chemical elements were extracted from Ion Beam Analysis. A systematic study was performed to see how the photoconductive and photochromic responses of the REMHO thin films depend on the wavelength and intensity of the illuminating light as well as the chemical composition of the films. Both effects showed i) higher response for shorter wavelength, ii) a cut-off near a similar wavelength, iii) saturation near UV region, and iv) similar relaxation time but with different kinetics. Multiple measurements performed on the same sample showed that the previous measurement affects the next measurement indicating a memory effect. Finally, the photoconductive response showed an increase with increasing oxygen concentration.
Acknowledgments

I would like to start by thanking my supervisor, Dmitrii Moldarev for his great supervision, patience, encouragement, and for allowing me to work independently while always being available to help me out when needed. I express my deep gratitude to my subject reader, Prof. Max Wolff for giving me the chance to work on such an interesting topic and for his kindness, inspiration, valuable feedback, and guidance throughout this thesis.

My sincere acknowledgment goes to Prof. Daniel Primetzhofer for attending every photochromic meeting and sharing his ideas to help me explain my results. I convey my thankfulness to Marcos Moro as well for showing enthusiasm, offering help whenever he could, and for all the knowledgeable discussions that he shared with me. Thanks to my colleagues from the photochromic group, who worked on this topic before me which gave me directions, and those who worked in parallel with me for all their contributions. I must mention the cooperative, warm, and friendly behavior I received from everyone from the Ion Physics research group and Tandem Laboratory. I wish all the best to this research group with amazing people.

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**Populärvetenskaplig sammanfattning**


Ett nytt tillägg till de fotokromiska materialen är de tunna filmerna av syrehaltiga sällsynta jordartsmetalhydrid (REMHO) (se bild 1b). De visar snabb växling och arbetar under ett brett spektrum av solljus från infrarött till ultraviolett. Under denna fotokroma effekt ökar också materialets elektriska ledningsförmåga drastiskt vilket kallas fotokonduktivitet. Dessa unika egenskaper hos dessa material kan användas i en mängd applikationer, inklusive vätelagring, optiska sensorer, energisparande smarta fönster etc. För fysiker är det viktigt att studera dessa material inte bara för att förstå den bakomliggande fysiken. Detta forskningsarbete syftar till att förstå sambandet mellan fotokonduktivitet och fotokromism hos dessa material.


![Figure 1. a) En illustration av fotokrom effekt på glasögon vid olika grader av exponering för solljus. (bildkälla: internet [1]), b) Fotokrom effekt på en REMHO tunn film. Provet exponerades för starkt ljus och halva provet hölls täckt. Mörkningen av den avtäckta delen syns tydligt på fotot.](image)
Popular Science Summary

Photochromic glasses and lenses are popular among people who enjoy outdoor activities. As their name suggests, they change tint or color (chromo) under exposure to light (photon). These glasses are clear when used indoors or in dull weather. However, they darken and act like sunglasses when worn outdoors under bright sunlight (see Fig. 1a). Runners, skiers, and cyclists use these glasses to protect their eyes from harmful UV rays from the sun. Most photochromic glasses in the market are organic. The major restraint of the existing photochromic materials is that they are not long-lasting if frequently used outdoors. On hot summer days, they do not give enough coverage like regular sunglasses. There is still a plethora of room for improvement regarding the existing photochromic materials.

A new addition to the photochromic materials is the thin films of oxygen-containing rare-earth metal hydrides (REMHO) (see Fig. 1b). They show fast switching and work under a broad range of sunlight from infra-red to ultraviolet. During this photochromic effect, the electrical conductivity of the material also increases drastically which is known as photoconductivity. These unique properties of these materials can be utilized in a plethora of applications including hydrogen storage, optical sensors, energy-saving smart windows, etc. To physicists, studying these materials is crucial not only for their applications, but also to understand the underlying physics. This research work is aimed at understanding the correlation between the photoconductivity and photochromism of these materials.

In this work, it has been found that both the photoconductive and the photochromic effects increase with the energy of the light. Both effects require a minimum energy of light to exhibit a significant effect. When the light is removed, the samples take at least a few minutes to recover from both the optical and electrical change caused by illumination. This suggests that just like the photochromic effect, the photoconductive effect is also not a purely electronic process. Our results are in line with a study by Hans et al. They reported the existence of two different phases in the microstructure of the REMHO thin films and hypothesized that the photochromic effect can originate from the transfer of hydrogen between the two phases. Moreover, one of the results of this project shows memory effect of the REMHO thin films i.e., the influence of previous illumination on the next illumination. It is also found that these two effects are regulated by the chemical composition of the films in a slightly different manner. In conclusion, these two effects, even though not being entirely similar, correlate to a great extent.

An illustration of the effect on glasses under different degrees of sunlight exposure can be found in Fig. 1a. Photochromic effect on a REMHO thin film can be seen in Fig. 1b. The sample was exposed to strong light keeping half of the sample covered. The darkening of the uncovered part is visible in the photo.
List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>APT</td>
<td>Atom probe tomography</td>
</tr>
<tr>
<td>DC</td>
<td>Direct current</td>
</tr>
<tr>
<td>fcc</td>
<td>Face-centred cubic</td>
</tr>
<tr>
<td>IBA</td>
<td>Ion beam analysis</td>
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<tr>
<td>LED</td>
<td>Light emitting diode</td>
</tr>
<tr>
<td>NMR</td>
<td>Nuclear magnetic resonance</td>
</tr>
<tr>
<td>PC</td>
<td>Photochromic</td>
</tr>
<tr>
<td>PVD</td>
<td>Physical vapor deposition</td>
</tr>
<tr>
<td>REMHO</td>
<td>Oxygen-containing rare-earth metal hydride</td>
</tr>
<tr>
<td>ToF-E ERDA</td>
<td>Time of flight-energy elastic recoil detection analysis</td>
</tr>
<tr>
<td>UV</td>
<td>Ultraviolet</td>
</tr>
<tr>
<td>XRD</td>
<td>X-ray diffraction</td>
</tr>
<tr>
<td>YHO</td>
<td>Oxygen-containing yttrium hydride</td>
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</table>
## Terminology

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tbody>
<tr>
<td><strong>Photodarkening</strong></td>
<td>Decrease in the transmittance of a material under illumination</td>
</tr>
<tr>
<td><strong>Bleaching</strong></td>
<td>Sample recovering from photodarkening to its initial state</td>
</tr>
<tr>
<td><strong>Band gap</strong></td>
<td>An energy range in solids where no electronic states can exist</td>
</tr>
<tr>
<td><strong>Dichroic mirror</strong></td>
<td>Mirror having significantly different transmittance or reflectance for two different wavelength regions</td>
</tr>
<tr>
<td><strong>Fermi energy level</strong></td>
<td>Highest energy level of a material occupied by electrons at absolute zero temperature</td>
</tr>
<tr>
<td><strong>Longpass filter</strong></td>
<td>Filter which only transmits wavelengths longer than a cut-off</td>
</tr>
<tr>
<td><strong>Photochromism</strong></td>
<td>Reversible change in the optical properties of a material upon exposure to optical radiation</td>
</tr>
<tr>
<td><strong>Photoconductivity</strong></td>
<td>Change in electrical conductivity upon exposure to electromagnetic radiation</td>
</tr>
<tr>
<td><strong>Rare-earth metals</strong></td>
<td>Sc, Y, and elements in the Lanthanide series</td>
</tr>
<tr>
<td><strong>Reactive Magnetron Sputtering</strong></td>
<td>Plasma based thin film deposition technique where atoms are knocked out from a target and deposit on a substrate in the presence of a reactive gas</td>
</tr>
<tr>
<td><strong>Substrate</strong></td>
<td>The base on which thin films are deposited e.g., glass</td>
</tr>
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1 Introduction

Rare-earth metals are best known for their magnetic properties and have been widely used as strong permanent magnets in various electro-mechanical devices. [2] They are a group of 17 elements in group III in the periodic table namely Sc, Y, and the elements in the lanthanide series. Rare-earth metals are not as rare as their name suggests. They are quite abundant on earth and are contained in most minerals in small concentrations. [3, 4] Yet, they were difficult to mine and process. [4, 5]

The discovery of the optical and electrical properties of the hydride compounds of rare-earth metals are comparatively new. [6–10] O-containing rare-earth metal hydride (REMHO) thin films are one of the very few inorganic compounds that exhibit a photochromic effect [10] i.e., reversible change in optical transmission upon illumination with light. After their discovery, understanding the structure and mechanism of the photochromic effect of these materials has been an intriguing research area for many physicists over the last decade. These materials also show a gigantic drop (3 to 5 orders of magnitude) in resistivity instantly under illumination. [9, 11] Their photochromic and photoconductive properties can be exploited to develop high density memories, optical displays, logic gates, optically switchable transistors, smart windows, data storage, optical sensors, etc. [9, 12–16]

1.1 A Look into the History

The discovery of metal to insulator transition of rare-earth metal hydrides was first mentioned in a handbook in 1995. [6] However, no information on changes in optical properties was provided there. Later in the same year, it was reported in the PhD thesis of J.N. Huiberts that shiny metallic mirrors of yttrium\(^\text{a}\) turn into a transparent yellowish sample due to hydrogen uptake at 200 K temperature in a high-pressure diamond anvil cell. [7] This gasochromic behavior of the yttrium hydride thin film was controlled by the pressure of the hydrogen gas. Meanwhile, Ouwerkerk et al. found that the hydrides of other rare-earth films also exhibit radical changes in optical properties during the transition from metal to insulator. [17] Later on, UV light-induced metal-insulator transition in yttrium hydride films was noticed by Hoekstra et al. in 2001 at very low temperature (<50K). [8] In 2007, the photochromic effect in yttrium hydride was discovered by Ohmura et al. when a sample was under illumination with visible laser light at room temperature and high pressure (5.8 Gpa). [10] From X-ray diffraction (XRD) measurement, they found the formation of fcc \(YH_2\) and hexagonal \(YH_3\) in the foil and proposed that the coexistence of these two phases is critical for the photochromic effect since single phase \(YH_3\) sample did not show photochromism. [10] They also proposed that near the interfaces of \(YH_2\) and \(YH_3\), lattice defects or hydrogen defects can facilitate site-to-site hydrogen relocation which can be the mechanism of this photochromic effect. [10] In 2011, Mongstad et al. observed a photochromic effect associated with photoconductivity in oxygen-containing yttrium hydride (YHO) thin films at ambient conditions and moderate intensity of visible and UV light. [9] They also reported that this effect is color-neutral and can be related to the considerable amount of oxygen in the film. Later, photochromism in several other rare-earth metals (Gd, Nb, Dy, Er, etc) has been reported during the last decade. [14, 18]

\(^\text{a}\)Yttrium was first discovered in ‘Ytterby Mine’ near Stockholm, Sweden. [4]
1.2 Purpose of this Project

The aim of this research work is to understand the photochromism and the photoconductive behavior of the REMHO thin films and fathom out the correlation between them. This thesis is a continuation of my previous project (see Ref. [19]) where some qualitative relations between these two phenomena were established. In this work, a more systematic approach was taken to reveal the extent of their correlations quantitatively. The existing setup had some limitations such as the inability of the optical setup to record the transmittance of the film during photodarkening and heating of sample inside the resistivity box during illumination. These technical issues have been overcome by adding extra optical parts to the optical setup and modifying the resistivity setup. Some other scientific questions, for example, the effects of heating of the samples during illumination and the contribution of the thermo-induced conductivity to the overall increase of conductivity of the samples, have been investigated. Moreover, samples of different chemical compositions have been illuminated with light of different wavelengths and intensities while simultaneous optical and electrical measurements were performed. The results were analyzed, and the differences and similarities of the photoconductive and the photochromic responses from all experiments were discussed.

This thesis consists of several main sections and is organized in the following manner. In Section 1, the introduction and the objectives of this research work are given. Section 2 contains a brief review of the background theoretical concepts which will help the reader to follow the later sections. Section 3 provides information about the method used for the sample synthesis. The experimental setup used for the characterization of the samples and some upgrades in the existing setup are described in Section 4. The results of this work are presented in Section 5 and discussed in Section 6. Finally, the takeaways from this project and possible implications are briefly described in Section 7.

2 Concepts

An overview of theoretical concepts which are relevant for the understanding of this research work is included in this section. Details can be found in the references mentioned in the respective parts.

2.1 Band Theory of Electrical Conductivity

Solid materials are divided into three main categories (metal, semiconductor, and insulator) according to their electrical conductivity. Metals have delocalized electrons moving freely inside them. They conduct electricity with minimum impedance. On the other hand, insulators cannot carry any significant electric current because of not having mobile charges. Semiconductors have electrical properties in between metals and insulators. Metals can conduct electrons even at 0 K temperature unlike semiconductors and insulators.
The electrical conductivity of metals, semiconductors, and insulators can further be explained by band theory. This theory suggests that molecular orbitals in solids overlap and form a series of energy bands. The energy levels within a band are considered continuous unlike the energy level of an atom in isolation, which is discrete. In solids when a large number of atoms come close to each other, the total number of atomic orbitals becomes extremely large. The energy difference between the orbitals can become comparable to the energy that electrons constantly exchange with phonon. That is why energy levels form continuous bands in solids. There are some ranges of energy an electron cannot have, which are called forbidden bands or band gaps. The most energetic occupied band is called the valence band, and the lowest energy unoccupied band is called the conduction band.

Metals, semiconductors, and insulators can be distinguished by the location of electron bands with respect to the Fermi level. Fermi level is the highest occupied energy level of material at absolute zero temperature. In metals, the valence and the conduction bands overlap leaving no band gap (See Fig. 2) which makes them good conductors of electricity. On the other hand, the band gap in an insulator is too large for electrons to overcome under normal circumstances. In semiconductors, the band gap is small. Electrons in semiconductors can be excited into the conduction band from the valence band by different processes including thermal or photon excitation.

Upon heating, electrons in the valence band of semiconductors can jump into the conduction band. This generates holes (missing electrons) in the valence band. Both these free electrons in the conduction band and holes in the valence band are the charge carriers of the semiconductors. Heating not only increases the carrier concentration in semiconductors but also the carrier mobility. Thus, we observe thermo-induced conductivity in semiconductors. Furthermore, electrons can also be elevated from valence band to conduction band by absorbing a photon with energy larger than the bandgap. This process results in an increase in conductivity of semiconductors which is known as photoconductivity.
2.2 Photochromism in REMHO Thin Films

Recently discovered photochromism in REMHO thin films is different from the photochromism in transition metal oxides [23] where the latter is involved in charge transfer mechanism [24] or small polaron absorption. [23] Scientists have been trying to reveal the origin and mechanism of this exceptional optical property in REMHO thin films. Below are some hypotheses made by different research groups to explain the mechanism behind their photochromism.

When the very first time, photochromism in YHO was discovered, it was reported that for YHO films with a bandgap of 2.6 eV, photon excitation with light of lower energy than 2.6 eV such as green or red was able to trigger photoconductivity. [9] This indicates that this is not a purely electronic process rather involves the presence of defect states or an Urbach tail as described in Ref. [25]. Data from the nuclear magnetic resonance (NMR) experiment suggested that initially transparent YHO thin films hold three hydrogen species having different mobilities. [23] They proposed that the hydrogen species with the highest mobility gets trapped while illuminated and is released when illumination is stopped. [23] X-ray diffraction data demonstrated that lattice contraction occurs in the crystal structure of the samples under illumination. [26]

You et al. reported that the increase of deposition pressure increases the optical band gap and decreases the photochromic response. [27] Further works on the chemical composition dependence of the photochromic response of YHO were performed by Moldarev et al. where they proposed an empirical chemical formula $YH_2-\delta O\delta$ for the YHO films. Here, $\delta = [O]/[Y]$ which is the measure of oxygen concentration in the film. They observed that photochromic response persists within the range of $0.45 < \delta < 1.5$ with maximum response near $\delta = 0.5$. [28, 29] Their experiment also proved that hydrogen atoms are replaced by oxygen when oxidized due to annealing or air exposure. [28] On the other hand, Cornelius suggested another formula, $REO_xH_{3-2x}$ considering stable compounds, stoichiometry, and charge neutrality. [30] Here, x is the oxygen concentration with a range $0.5 \leq x \leq 1.5$.

Time-dependent density functional theory based simulation showed the formation of photo-induced dihydrogen defects on the ultrafast timescale ($\approx 100$ femtoseconds) in the films which can act as a donor and be responsible for photochromism. [31] The bulk nature of the photochromic effect in YHO thin films was reported in Ref. [32] A recent study by Hans et al. of O-containing gadolinium hydride thin films using atom probe tomography (APT) discovered the formation of dual-phase in the microstructure of the material which are an oxygen-rich insulating phase and a hydrogen-rich metallic phase. [25] According to their hypothesis, a hydrogen transfer between the phases may be the mechanism of photochromism. [25] It is the same hypothesis as Ohmura et al. made to explain photochromism in pressurized yttrium hydride foil. [10] A recent study by Moldarev et al. reported hydrogen release during illumination of a freshly grown YHO sample and found a linear relationship between the photon energy and photochromic response. [33]
3 Thin Film Synthesis

For this work, yttrium was chosen as the representative of rare-earth metals. In this section, a brief description of the method used to grow the YHO thin films is given. Moreover, the growth conditions for developing uniform samples with high photochromic response are discussed.

3.1 Reactive Magnetron Sputtering

Samples for this project were synthesized by reactive magnetron sputtering which is a plasma-based physical vapor deposition technique (PVD). Theoretical description and detailed working principle of this technique can be found in Ref. [34–37]. Samples were grown in the Balzer Union DC magnetron sputtering system. A yttrium disc (99.99% pure) was set up as the target in the upper part of the sputtering chamber connected to the cathode and glass substrates were mounted on the substrate holder (see Fig. 3). A high vacuum ($10^{-5}$ mbar) was created in the chamber prior to the deposition by a turbo pump. Then, a small amount of Ar and $H_2$ gas (pressure $10^{-3}$ mbar) was introduced into the chamber. The nominal purity of the hydrogen gas was 99.998%. A negative voltage was applied to the target to ignite a plasma. During the sputtering process, energetic ions bombard the target and dislodge yttrium atoms which react with $H_2$ and deposit on the substrate as yttrium hydride. Upon air exposure, some hydrogens are replaced by oxygens [38] and thus, yttrium hydride transforms into YHO. The same setup and process were used in the work of Ref. [18, 19, 39] which can be followed for more technical details.

Fig. 3 is an illustration of the sputtering process inside a sputtering chamber followed by oxidation outside.

![Figure 3. A sketch of the sample growth process using reactive magnetron sputtering.](image)

The growth parameters of the samples grown in this project is tabulated in Table 1. The depth profiles of the samples can be found in Appendix I.
Table 1. Growth conditions of the samples.

<table>
<thead>
<tr>
<th>Batch #</th>
<th>Date of deposition</th>
<th>Target distance, cm</th>
<th>Base pressure, 10^{-5} mbar</th>
<th>Hydrogen flow, arb. unit</th>
<th>Growth pressure, 10^{-3} mbar</th>
<th>Growth time, sec</th>
<th>Current mA</th>
<th>Color of the films</th>
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<td>8</td>
<td>2100</td>
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<td>6</td>
<td>3</td>
<td>20</td>
<td>8</td>
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<td>8</td>
<td>1800</td>
<td></td>
<td>yellow</td>
</tr>
</tbody>
</table>

4 Setup for Characterization

The REMHO thin films were characterized optically, electrically, and with respect to their chemical composition during this project. The optical characterization was done with the help of a UV-vis spectrometer and white probing light whereas electric transport investigation was done with a resistivity setup. Time of flight-energy elastic recoil detection analysis (ToF-E ERDA) was employed for the chemical characterization using a 5 MV NEC PELLETRON accelerator at Tandem Laboratory, Uppsala University. In this section, information about the optical and the resistivity measurement setups is presented. Details about ion beam analysis (IBA) and determining the chemical composition of similar REMHO films can be found elsewhere. [28, 29, 40]

The initial versions of the optical and resistivity setups have been developed in the works of Refs. [11, 19], respectively. During this project, there have been some upgrades and extra features added to the setup which will be discussed in this section. The sensitivity of the setup has been tested and the results can be found in Section 5.4. Fig. 4 shows different parts of the upgraded version of the optical setup.

4.1 Optical Setup Upgrades

For optical characterization, a UV-vis spectrometer was used to record the intensity of transmitted light. In this setup, white light from a compact stabilized tungsten halogen light source is used as a probe which is detected and recorded by a UV-vis spectrometer. Monochromatic LEDs are used as triggering lights to induce the photochromic effect in the samples. During this work, some extra optical parts were added to the system such as a dichroic mirror, a long pass filter, and different colors of LEDs which are discussed in the following two sections.

\(^b\) This batch of samples showed 78\% photochromic response after 10 min of illumination which is the maximum response achieved till now to the best of our knowledge.

\(^c\) This batch showed the quickest bleaching. More about this can be found in Sections 5.5.
4.1.1 Installing Dichroic Mirror and Longpass Filter

Dichroic mirror is also known as a dichroic reflector, beamsplitter, dual-band mirror, or dual-wavelength mirror. [41] It reflects light above a specific wavelength and transmits light below that cut-off. The dichroic mirror (DMLP650) which is added to the setup has 50% T/R at 650 nm. In the optical setup, it has been placed at 45° angle with respect to the probing light and the triggering light (see Fig. 4). It reflects the triggering light and directs it towards the sample to trigger the photochromic effect and at the same time transmits the probing light in the direction of the detector. A longpass filter (FEL0700) with a cut-on wavelength at 700 nm was installed in the setup which absorbs all wavelengths below 700 nm and transmits light of wavelength above it. The transmission spectra of the dichroic mirror and the longpass filter can be found in Fig. 30 in Appendix II.

4.1.2 Calibration of the LEDs

Five new LEDs with 5 wavelengths (365 nm, 405 nm, 455 nm, 530 nm, and 617 nm) were added to the optical setup. The LEDs are attached to a heat dissipation system. An adjustable focusing lens was attached to the LEDs. These LED lights have different maximum intensities. The intensities of the LEDs can be controlled by tuning the driving current. Thus, calibration was needed to relate the intensity to the corresponding currents. A pyranometer (Fig. 5b) was used for this purpose. It was a Kipp & Zonen CM11 model which is mainly used as a solar radiation sensor detector. It has a sensitivity of $4.83 \times 10^{-6} \text{V/Wm}^{-2}$. The pyranometer was connected to a multimeter to record
the potential difference produced by the thermopile inside the pyranometer due to light exposure. The irradiance was calculated by dividing this voltage by the sensitivity of the pyranometer. This irradiance was used as the measure of the intensity of the light. Then the intensities corresponding to different currents for a fixed wavelength were determined which is plotted below. (Fig. 5a)

Figure 5. a) Intensity as a function of current for LEDs of different wavelengths for a fixed distance (2cm) and maximum focusing, b) The Kipp & Zonen CM11 pyranometer.

4.2 Improving the Resistivity Measuring Setup

The investigation of the electric properties of YHO thin films was done by measuring the resistivity of the films by the two-point probe method. The two probing points in contact with the sample surface inside the sample holder can be seen in Fig. 6b & 6c. The setup used for this project to record the resistivity was developed during the work in Ref. [11] and later used in Ref. [19]. In the older version of the resistivity setup, the samples were placed inside a confined box with black walls (see Fig. 6). There were some issues (e.g., increase of temperature of the film due to illumination) in the existing setup which were reported in Ref. [19]. During this project, the setup has been tested thoroughly and improved accordingly, which is described in this section.

New frames with open sides (Fig. 7a) were 3D printed to support the new focusing LEDs and assure that the heat due to illumination will dissipate efficiently. Moreover, the sample support that holds the samples has been modified. In the previous version, the probes were 1 mm off-sided on both edges of the hole through which the sample is illuminated. (Fig. 7b) A new bottom part of the sample support with a larger opening at the back part was 3D-printed to make sure that sufficient film area including the part right under the contacting points are darkened while illuminating the sample. (Fig. 7b) However, for this to work, the samples should be illuminated from the substrate side.
Figure 6. The initial version of the resistivity measuring setup developed during the work of Ref. [11]. a) Box with LED and fan attached on top where sample holder was placed at the bottom. b) & c) are the front and side view of the sample holder, respectively.

Figure 7. a) New frames for resistivity setup with open sides to allow heat to radiate out, b) The upper picture shows the previous sample holder with off-sided probes and the bottom picture shows the modified version of the sample support with a larger opening in the back part of the sample holder.
4.3 Combining the Optical and Resistivity Setup

The final upgrade of the instrumentation of this work was to enable simultaneous measurements of the photochromic and photoconductive response of the same sample. For this, the sample holder from the resistivity setup was placed in between the probing light and the detector in the optical setup. (Fig. 8) After attaching the sample inside the sample support, the two probing points transport the information about the electrical conductivity of the samples to the HP 4339B high resistance meter. While at the same time, the probing light from the optical setup sends information about the change in optical transmission to the spectrometer. Thus, both responses are recorded simultaneously. Fig. 8 illustrates a schematic diagram of the combined setup.

![Schematic diagram of the combined setup](image)

For optical and electrical characterization, photoconductivity and photochromism are defined according to the following equations.

\[
\text{Photochromism} = \frac{T_0 - T_f}{T_0} \times 100\%
\]

Where \( T_0 \) = relative transmittance of the sample before illumination and \( T_f \) = relative transmittance of the sample after illumination

Transmittance is denoted as the fraction of the light which is transmitted through the sample. It
is defined as the ratio of the averaged intensity of incident light to the averaged intensity of the transmitted light.

Relative transmittance = \( \frac{\text{Averaged intensity of the transmitted light}}{\text{Averaged intensity of the transmitted light before illumination}} \times 100\% = \frac{\langle I \rangle}{\langle I_0 \rangle} \times 100\% \)

Photoconductivity = \( \frac{R_0 - R_f}{R_0} \times 100\% \)

Where \( R_0 \) = initial resistivity of the sample before illumination and \( R_f \) = final resistivity of the sample after illumination

In this work, the resistance of a film recorded between two probing contacting points which are 1 cm apart, has been considered as a measure of the resistivity of the film in the unit of ohm/cm.

5 Findings

The results from different experiments of this project are delineated in this section. At first, the characteristics of different types of samples, depending on their chemical composition, are explained. Then, the outcomes from the experiments for achieving uniform films by adjusting the growth parameters are presented. The evolution of the temperature in the films due to illumination is described as well. Moreover, the dependence of the photoconductive and photochromic responses on the wavelength and intensity of the illuminating light is revealed. In the end, the dependence of these two phenomena on the chemical composition of the samples is reported.

5.1 Types of YHO Samples

The appearance and the properties of the samples are related to the chemical composition of the films. [29, 31, 40] The growth conditions of the films i.e., base pressure, target to substrate distance, partial pressure of Ar and hydrogen, current etc affect the microstructure of the films. This microstructure controls the oxidation rate of the films during air exposure. [18, 25, 29] Depending on the oxygen concentration in the films, samples can be of three different types: a) opaque, b) colored transparent and, c) fully transparent. (Fig. 9a-9c) The opaque samples are metallic and have oxygen concentration (\( \delta \)) below 0.5. Samples within the range of \( 0.45 < \delta < 1.5 \) are usually yellowish but some other colors such as pinkish and blueish samples have also been found which seems to depend on the thickness of the films. [19] The position of the absorption edge (band gap) also affects the appearance of the sample. Films with oxygen concentration above 1.5 are fully transparent and insulating.

None of the opaque and fully transparent samples show any photochromic response. However, when electrical measurements were performed, it turned out that all three types of samples show photoconductive effects. (Fig. 9d-9f) The highest photoconductive response was recorded for the photochromic samples. A systematic investigation of the relation of photoconductivity of samples
with their oxygen concentrations is reported in Section 5.7.

Fig. 9 shows the physical appearance of all three types of samples and their photoconductive responses.

(a) Opaque metallic $\delta < 0.5$  
(b) Photochromic semiconducting $0.5 < \delta < 1.5$  
(c) Transparent insulating $\delta > 1.5$

(d)  
(e)  
(f)

Figure 9. The appearance of all three types of samples (a-c) and their photoconductivity (d-f respectively). The blue shaded parts represent illumination.

5.2 Achieving Uniform Samples

For practical use, thin films are expected to show i) uniformity, ii) high photochromic response, and iii) fast switching. These qualities mostly depend on the growth condition of the films. [18] In this section, I report how the quality of the samples can be improved by controlling their growth conditions.

In the previous project [19], a significant difference (orders of magnitude) in the initial resistivity was noticed due to changing the two contacting points on the same sample. It was an indication that the films were not sufficiently uniform. In this project, I grew one batch of samples with a higher distance between the substrate and the target than before which increased the deposition area. For the growth condition of this batch, see batch 1 in Table 1. The samples turned out to be more uniform which was verified by determining the chemical composition of the sample taken from the middle and near the edge of the sample holder. The composition was determined by ToF- E ERDA
measurements. Both of the samples are found to have almost the same chemical compositions (Fig. 10). Furthermore, the resistivity at different points of the samples from this batch showed values in the same order of magnitude (Fig. 11) which again proves the uniformity of the film.

Figure 10. Visual appearance of thin films in the chamber after deposition.

Figure 11. Resistivity measurements taken in different spots as a function of time for different samples from the same batch.

5.3 Temperature Increase during Illumination

The temperature increase of the samples during illumination affected the measurement which was reported in Ref. [19]. Since resistance is temperature dependent, heating of the samples during illumination can contribute to the overall change in conductivity of the material. During this project, an investigation was conducted to study this effect more carefully to separate thermo-induced conductivity from the overall change of conductivity.
5.3.1 Temperature Evolution of the Film during Illumination

The temperature inside the setup due to illumination was checked with a Bosch GTC 400 C Professional thermo camera. Fig. 12 shows the photographs inside the box before and after the illumination with a 455 nm LED for 10 min. It showed that the bottom surface of the box heated up to 39.5° C which is 15° C above room temperature.

![Heated setup after 10 minutes of illumination observed by a thermo camera.](image)

Later, the evolution of the temperature of the samples during illumination was recorded using a thermocouple. It was found that the films can heat up to 10° C above the initial temperature. Heating can be partly reduced by adding a fan to the setup. The result was compared to a copper sheet of the same size which was illuminated simultaneously with the sample. The results are presented in Fig. 13. This modification makes our study of photoconductivity more reliable by reducing the contribution from thermally-induced conductivity.

![Temperature evolution of the films measured by a thermocouple.](image)

<table>
<thead>
<tr>
<th></th>
<th>Temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room temp</td>
<td>24.4</td>
</tr>
<tr>
<td>Initial temp of sample</td>
<td>25.1</td>
</tr>
<tr>
<td>4 month old sample Without fan</td>
<td>35.5</td>
</tr>
<tr>
<td></td>
<td>With fan</td>
</tr>
<tr>
<td>Fresh sample with fan</td>
<td></td>
</tr>
<tr>
<td>Copper sheet without fan</td>
<td></td>
</tr>
</tbody>
</table>
5.3.2 Contribution of Thermo-induced Conductivity

Next, I performed further experiments to see how much this change in the temperature of the film can induce conductivity. This was important to separate the contribution of thermal conductivity from the total photoconductive response. The samples were heated to different temperatures by an external heater and the evolution of resistivity was tracked (see Fig. 14). It was found that resistivity dropped by a factor of 10 of its initial value due to heating to $5^\circ \text{C} - 20^\circ \text{C}$ above the sample's initial temperature.

![Figure 14. Thermo-induced conductivity of the samples due to heating a) 32° C and b) 49° C temperature.](image)

YHO sample showed thermal conductivity like a semiconductor i.e., decrease in resistivity under heating. On the other hand, in my previous project, [19] I found that the resistivity of a darkened sample (due to illumination) increased with the increase in temperature of the film. This behavior shows the metallic characteristics of the darkened sample and the semiconducting characteristics of the undarkened sample which supports the semiconducting to metallic transition of the YHO samples under illumination.

5.4 Sensitivity of the Resistivity Setup

As the samples have high resistance, hence, low current at the given voltage (in the picoampere range). However, the resistance meter has a lower limit of current that it can record without substantial noise. As mentioned earlier, an additional fan was used to cool the sample. An investigation was done to check if the movement of the wires inside the box due to the fan or other motions, adds current to the system and affects the result. For this, the resistivity of the film was measured with and without the fan. There was no significant change of resistivity in these two cases, as shown in Fig. 15. Moreover, it was noticed that higher applied voltage reduces the noise in the data.
Figure 15. The difference in the measured resistivity of the film with and without cooling fan in two different applied voltages. The resistivity curve (red line) for the measurement with 30 V, is zoomed in and presented in a separate graph on the right hand side.

5.5 Wavelength Dependence

In the work of Moldarev et al., it was reported that illumination with higher photon energy (i.e., shorter wavelength) triggers a stronger photochromic response. [33] To check if this trend holds true for the photoconductive response, several identical samples were illuminated with lights of different photon energies, and their optical and electrical properties were measured simultaneously. Each sample was illuminated once with one specific wavelength of LED to avoid effect from any previous exposure. The wavelength dependence measurement was performed on two different batches of samples. The results are described below.

Experiment: 1

For this experiment, Batch-5 from Table 1 was used. Four identical samples from this batch were illuminated for 2 minutes by 4 different LEDs having wavelengths of 617 nm red, 530 nm green, 455 nm blue, and 405 nm violet i.e., 2.01 eV, 2.34 eV, 2.72 eV and, 3.06 eV of photon energies, respectively. The optical and resistivity measurements were carried out covering the whole photo-darkening and bleaching processes. The oxygen concentration for this batch of samples was $\delta = 0.99$. This batch of samples was grown 1 week before the measurements and kept in the desiccator. The evolution of the transmittance and resistivity of the films due to illumination with different wavelengths of light is plotted in Fig. 16. For calculating the transmittance of the film, the intensity of the detected light was averaged over 700-900 nm of wavelength in order to exclude any contribution from the triggering lights.

Both the photoconductive and the photochromic responses were higher for shorter wavelengths (Fig. 16c). This cut-off is most likely related to the band gap of the samples which depends on the oxygen concentration. [33] For this batch, the cut-off wavelength is in between green and red as we can see from Fig. 16a & 16b. Thus, the band gap is expected to be slightly over the energy of green light (2.34 eV) according to Ref. [33], where they observed cut-off wavelength slightly
below the bandgap. We also see a similar timescale in the relaxation curve for both responses. For a purely electronic process, relaxation timescale in minutes or even in seconds is too slow. Thus, the relaxation of the photoconductive response here can be an indication of the hydrogen diffusion hypothesis [25] as mentioned in Section 2.2.

Figure 16. The evolution of the a) transmittance and the b) resistivity of the films of the first batch before, during and after illumination with different wavelengths of light. c) Photochromic and photoconductive response vs wavelength of triggering light for 2 minutes of illumination with intensity $662.5 \text{ W/m}^2$.

**Experiment: 2**

The wavelength dependence measurements were repeated on the samples from Batch-9 in Table 1. The oxygen concentration of this batch is $\delta = 1.05$. This time, one more LED (365 nm UV of wavelength, i.e., 3.40 eV) was used, in addition to the 4 LEDs employed for the 1st experiment.
Five identical samples were freshly grown in one batch and measured immediately. These five samples were illuminated for 2 minutes by 5 LEDs of different wavelengths. During the measurement of one sample, other samples were kept in the evacuated desiccator to avoid their degradation.

Figure 17. Evolution of the a) transmittance and the b) resistivity of the films of the 2nd batch before, during and after illumination with different wavelengths of light. c) Photochromic and photoconductive response vs wavelength of triggering light for 2 minutes of illumination with intensity $124 \text{ W/m}^2$.

The results are shown in Fig. 17. Just like the previous batch, higher responses were noticed for shorter wavelengths with a saturation region near the wavelength of UV. (Fig. 17c). For this batch, neither green nor red light were able to trigger detectable photoconductivity (Fig. 17b) but 0.4% of photochromic response was noticed when illuminated by green light (Fig. 17a). This batch of samples has a cut-off at a lower wavelength (higher triggering photon energy) than the previous one which is somewhat expectable as this batch has a larger oxygen concentration. However, violet
light showed a higher response than the UV which is surprising. The experiment was repeated and the expected result (i.e., UV showing a higher response than violet) was observed. (Fig. 31 in Appendix II) Later it was found that the sample used for the 1st measurement with violet light, had quite lower initial transparency compared to other samples. (Fig. 32 in Appendix II)

Note that the bleaching of the samples of this batch was exceptionally fast compared to other samples as we can see from Fig. 17a & 17b. The films recovered to 96-98% of their initial transmittance within 1 minute. This is the fastest relaxation ever seen. As mentioned before, the samples were not exposed to air for a long time before illumination which could be a reason for this fast recovery. Depth profile of this batch of samples can be found in Fig. 28 in Appendix I.

5.6 Intensity Dependence

Photon flux dependence of the photochromic effect was mentioned in the Ref. [33]. In this work, I performed measurements to find the intensity dependence of the photoconductive response of the REMHO samples. Two batches of samples (Batch-3 and Batch-4, respectively from Table 1) were used for this part of the research. The results are described below.

Experiment: 1

For intensity dependence measurement, an LED with a fixed wavelength (455 nm) was used. Four identical samples (Batch-3 from Table 1) were illuminated with four different intensities: 580 W/m², 1835 W/m², 1367 W/m², and 1822 W/m². Each sample was illuminated only once with a light of a specific intensity to avoid the memory effect, i.e., influence from the previous measurement.

![Figure 18. Intensity dependence of the a) photochromic and b) photoconductive response after 2 minutes of illumination.](image)

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19
From the optical data in Fig. 18a, we can see that a higher photochromic response corresponds to higher intensity. However, for the photoconductivity response in Fig. 18b, even though the lowest intensity shows the lowest response, we see an overlap for intensities higher than 1000 W/m². It can be because of the temperature rise of the samples during illumination. The increase in response with higher intensities was seized by the increase in resistivity due to the associated rise in temperature. That would mean that the photoconductivity effect is temperature-dependent, but photochromism is not. It can also be the case that the difference was too small to be visible in the log scale and with such high noise.

**Experiment: 2**

The intensity dependence experiment was repeated with a 405 nm violet light. The intensities were adjusted at smaller values than before (207 W/m², 414 W/m², 683 W/m²). For this experiment, one sample from Batch-4 was illuminated three times with three intensities for 3 minutes each time. After each measurement, the sample was allowed to bleach back to at least 97% of its initial transparency before performing the next measurement. The results show that if the order of measurement is from low to high intensities, then both responses increase with intensity. (Fig. 19) Then, the experiment was repeated with an identical sample starting from illumination with the highest intensity followed by the lower two intensities in sequence. The results showed a significant increase in the response for the lower intensities for example the photochromic response increased from 17% to 32% for 207 W/m² when illuminated in reversed order. (Fig. 20) So, the order of illumination affects the magnitude of photochromic response, indicating a memory effect which can again be related to the hypothesis of hydrogen transfer. [25]

![Figure 19](image1.png)  
(a) Relative Transmittance (%)

![Figure 19](image2.png)  
(b) Resistivity (Ω/cm)

Figure 19. Intensity dependence of the a) photochromic and b) photoconductive response after 3 minutes of illumination starting from low intensity and proceeding towards high intensity.
5.7 Chemical Composition Dependence

The photochromic effect of YHO thin films can be tuned by controlling the chemical composition of the films. [42] As mentioned in Section 3.2, the photochromic response of REMHO films is noticeable for oxygen to yttrium ratio within the range of 0.45 to 1.5. [28] To study the dependence of photoconductivity on the oxygen concentration of the YHO films, I grew one batch of identical opaque samples (see Batch-7 in Table 1). The samples were then annealed at 250° C temperature for different time durations (around 20 minutes difference in the duration of annealing between the samples). The annealing process removed hydrogen from the films and incorporated oxygen. In this way, a series of films of the same thickness but different oxygen concentrations were prepared. (Fig. 21) The chemical composition of the films was measured by ion beam analysis (i.e., Time of flight-energy elastic recoil detection analysis (ToF-E ERDA)) and the data was analyzed using software named POTKU. [43] The oxygen concentrations of the series of films were found to be, $\delta = 0.47, 0.57, 0.85, 1.08$. After composition analysis, the optical and resistivity measurements were done on these four samples.

![Figure 20. Intensity dependence of the a) photochromic and b) photoconductive response after 3 minutes of illumination starting from high intensity and proceeding towards low intensity.](image)

![Figure 21. Producing sample series with different chemical concentration but same thickness by annealing opaque samples for different time durations.](image)

![Figure 22. Producing sample series with different chemical concentration but same thickness by annealing opaque samples for different time durations.](image)

Fig. 22 shows the results from the oxygen concentration dependence measurements. The transmission through the two most opaque films ($\delta = 0.47, 0.57$) was too small to be recorded and therefore is not presented in the graph. The samples with the lowest two oxygen concentrations
did not show any photochromic response. The samples with $\delta = 1.08$ showed the highest response which decreased for $\delta = 0.85$. It agrees with the chemical composition dependence studies on the photochromic response of these materials mentioned earlier. [28, 29] In Fig. 22d, we see that photoconductive and photochromic responses do not show exactly similar dependence on chemical composition. Photoconductivity kept increasing with the increasing value of oxygen concentration while photochromism showed a decrease after a cut-off. The graph of the resistivity evolution of the sample with the lowest oxygen concentration has been presented in a separate plot (Fig. 22c) because of its very low value compared to the other 3 samples. Plots of absolute values of the normalized intensity over time can be found in Fig. 33 in Appendix II.

![Graphs showing the evolution of transmittance, resistivity, and photochromic and photoconductive response vs oxygen concentration.](image)

Figure 22. a) Evolution of the transmittance of the films before, during and after illumination with different wavelengths of light. b) & c) Evolution of resistivity of the corresponding films. d) Plot of the photochromic and the photoconductive response vs oxygen concentrations of the samples for 5 minutes of illumination.
It is also important to note that the initial resistivities of the four samples are in the range of several kΩ, MΩ, GΩ, and TΩ from lower to higher oxygen concentrations, respectively. The plot in Fig. 23 shows the resistivity of the films as a function of their oxygen concentrations. This supports the gradual transition of the films from metallic to insulating phase with higher oxygen concentration.

Figure 23. Oxygen concentration vs initial resistivity of the films.
6 Correlating Photoconductivity with Photochromism

The initial investigations of this project showed that all YHO samples (opaque, photochromic, or insulating) show photo-induced conductivity irrespective of their photochromism. However, this does not rule out that these two phenomena can be coupled. In fact, the highest photoconductive response was found for the photochromic samples which shows some relevance of these two phenomena. Later, a significant correlation was observed during the wavelength dependence measurements. Both effects showed higher response for shorter wavelength, a cut-off near a similar wavelength, and saturation near the UV region. These common characteristics could be related to the band gap of the YHO samples. Both effects can be visible for the energy of light slightly lower than their band gap as mentioned before which suggests the involvement of other processes during illumination. The reason can also be the presence of different kinds of defects in the films. Furthermore, both effects recovered close to the initial value almost at the same time but the relaxation curve did not follow the same time evolution. The recovery time scales for both of the effects were in the range of minutes which shows that both of the effects are not only electronic. If these effects involve an elemental transfer, hydrogen transfer along the dual-phase of the film is the most probable case as mentioned earlier. Our results are in line with the hydrogen diffusion hypothesis claimed by Hans et al. [25]

Both responses being affected by its previous exposure is another finding of this project which validates that none of these effects occur only due to electronic transfer. It was found when one sample which was previously exposed with high intensity of light showed a higher response than an identical sample for exposure with the same intensity of light. This memory effect can be related to the hydrogen diffusion hypothesis. If a sample is illuminated with high intensity, a large amount of hydrogen might be transferred during illumination to another phase. Probably, in this case, not all hydrogen atoms can return to their previous phase while relaxing. Some of them can still be at the boundary. This might have happened when the sample was illuminated with high intensity at first. So, in the next cycle, even with low intensity, the response was higher. As both effects showed this memory effect, the hydrogen diffusion can be the possible origin of both of these effects.

The measurement which did not agree quite well with each other is the chemical composition dependence of the photoconductive and photochromism. The chemical dependence of the photochromic effect is known which shows a decrease with higher oxygen concentration. Our study showed a different trend for photoconductive effect i.e., increase of response with oxygen concentration. However, only four samples were used which clearly did not cover the whole range of oxygen concentration. Thus, the full trend of the chemical dependence of photoconductivity is yet to be discovered. Finally, it can be said that the two phenomena definitely are correlated but they can have different kinetics. One of them can involve some more physical processes than the other one.
7 Conclusions

Photochromic REMHO materials deserve careful perusal since they are interesting for both fundamental and applied research in physics. The main objective of this was to find the correlation between the photochromic and the photoconductive effect these materials exhibit. For this, YHO thin films were produced by reactive magnetron sputtering and characterized chemically, optically, and electrically. The characterization was done by employing ion beam analysis, UV-vis spectroscopy, and two-point probe resistivity measurements, respectively. During this work, samples with a photochromic response of as high as 78% were produced and the fastest ever recovery was observed. Additional capabilities have been added to the optical setup such as illumination with different wavelengths and intensities of light and recording the transmittance of samples during photodarkening. The setup for the electrical characterization has been tested for the heating effect on samples during illumination and improved by 3D printing a new setup box with open sides. Finally, the optical and the electrical setup have been merged to allow simultaneous optical and electrical measurements.

All YHO thin films (opaque, photochromic, or fully transparent) show photoconductivity with the highest response for the photochromic ones. A notable correlation between some features of the photochromism and the photoconductive response has been observed in this project. From the wavelength dependence experiment, both effects showed higher responses for shorter wavelengths i.e., higher photon energy. Both effects also showed a cut-off wavelength and a saturation near the UV region. This means photoconductivity and photochromism of YHO thin films have a significant degree of correlation. Besides, the time scale of the relaxation curve of the photoconductive response supports that it is not a purely electronic process and elemental diffusion under illumination can be related to it. In addition, it has been found from a measurement with a series of different intensities of light on the same sample that both effects are influenced by the order of measurements. This indicates that the sample has a memory effect from the previous measurement. Furthermore, the results from the dependence of chemical composition of the two effects do not agree with each other. The chemical composition dependence of photochromism is already known but the photoconductivity reveals an opposite dependence.

In conclusion, photoconductivity and photochromism of the REMHO materials show significant correlations even though they might have different kinetics. Further implications of this thesis could be to perform research to see the dynamics of elements at the atomic level during illumination to validate the hypothesis of hydrogen transfer between phases. The memory effect observed during this project should also be investigated further such as how long this memory effect persists or if there is any cut-off energy to induce the memory effect. Moreover, samples with a broad range of chemical compositions can be used to achieve a complete picture of the chemical composition dependence of the photoconductive effect.

The main results from this work have been orally presented in two different conferences: i) International Conference on Physics for the centenary celebration of the University of Dhaka, Bangladesh, and ii) Nordics Physics Days 2021 hosted by Uppsala University, Sweden.
8 Appendices

8.1 Appendix I: Depth Profiles

The data for this section was obtained from ToF E-ERDA measurement and analyzed by the software, POTKU. [43] The blue and the red vertical bars represent the range of depth within which the compositions are calculated. The region near the surface (which is always rich in oxygen) is ignored since both photochromism and photoconductivity are reported to be a bulk effect. [19, 32]

![Figure 24](image1.png)  ![Figure 24](image2.png)

Figure 24. Depth profiles of two identical samples from Batch-1 described in section 5.2. a) sample grown in the middle, b) sample grown at the edge of the batch.

![Figure 25](image3.png)

Figure 25. Depth profile of a sample from Batch-3.
Figure 26. Depth profile of a sample of Batch-5.

Figure 27. Depth profile of a sample of Batch-6.

Figure 28. Depth profiles of two identical samples (a & b) from Batch-9 used in the wavelength dependence measurement (2nd experiment) described in section 5.5.
Figure 29. Depth profiles of the sample series created by annealing the samples of Batch-7.
8.2 Appendix II: Additional Plots

Figure 30. Transmission spectra of a) DMLP650 dichroic mirror and b) FEL0700 longpass filter. [44, 45]

Figure 31. The follow-up experiment of the wavelength dependent a) photochromic and b) photoconductive response (see Section 5.5, Experiment 2) for UV and violet light repeated on Batch-9 after 1 week.
Figure 32. The absolute values of the initial averaged intensities of the lights through the films used for the wavelength dependence experiment 2.

Figure 33. The absolute values of the averaged intensity of the lights through the annealed films of Batch-7 from the chemical composition dependence measurement. The curves for $\delta = 0.57$ and $\delta = 0.47$ are not noticeable in the graph as the values were too small.
9 Bibliography


