Nonlinear Oxide Materials for Quantum Photonic Circuits

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Introduction

Nonlinear optical materials exhibit non-linear responses of the frequency, polarization, phase or path of incident light, meaning that their response strength is not proportional to the light intensity or the interaction distance. These materials are used in devices such as optical switches, modulators, quantum light sources and optical waveguides. Examples include Lithium Iodate ($LiIO_3$), Lithium Triborate (LBO) and **Indium Tin Oxide (ITO)** [1].

Devices made from **nonlinear optical materials** are typically integrated into **Photonic Integrated Circuits (PICs),** which is a miniature chip containing two or more photonic components. **PICs** are used for converting optical signals into electrical signals by amplifying the frequency of light so are often integrated with other electronic components for sensing, imaging, optoelectronics and quantum computing.

Challenges and Project Aims

The integration of **nonlinear optical materials** into **PICs** is not well developed, and the fabrication of materials that exhibit strong optical non-linearity under low-power illumination is difficult [2]. This project aims to address these issues by fabricating **ITO thin films** using **Pulsed Laser Deposition (PLD)**, as **ITO** has promising **optical properties** that may be harnessed even with low-power illumination.

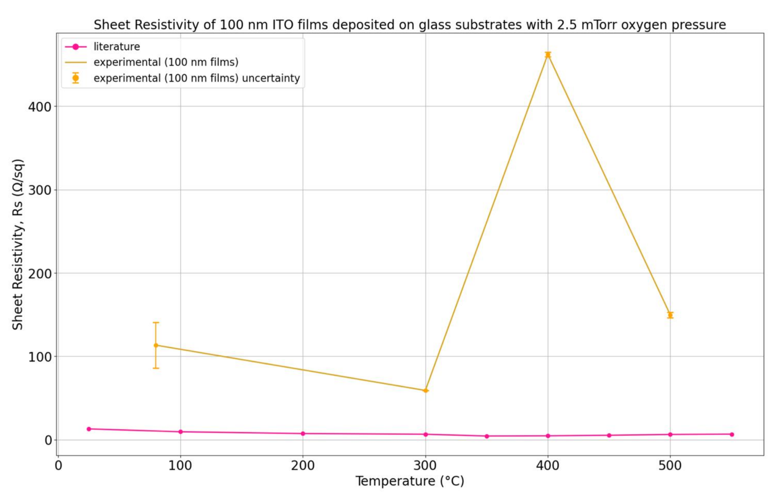
PLD is a physical vapour deposition technique in which a high-energy laser beam vaporises the target material into a plasma plume. The plume coalesces and self-assembles into a thin film on the substrate [3, 4].

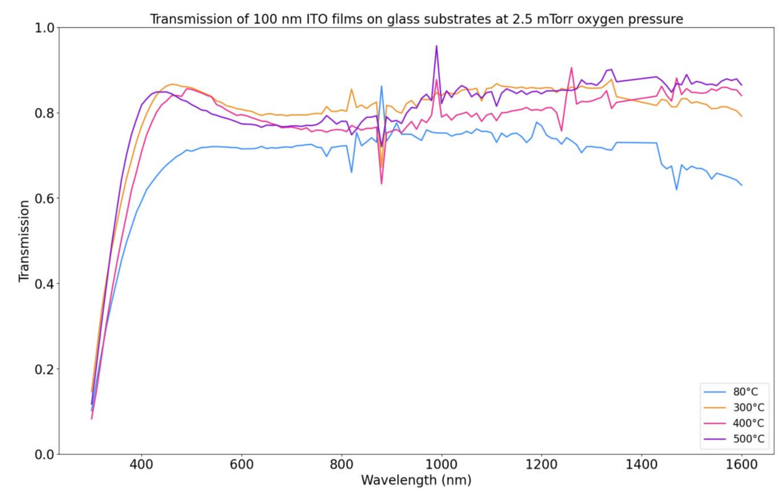
The films will be characterised to assess their **optical** and **electrical properties**, **crystallinity** and **surface morphology** to evaluate their potential for **PIC** integration and optical-to-electrical signal conversion.

Research: Temperature Series

100 nm **ITO thin films** were deposited on glass substrates at temperatures between 80°C and 500°C using **PLD** in a 2.5 mTorr oxygen atmosphere.

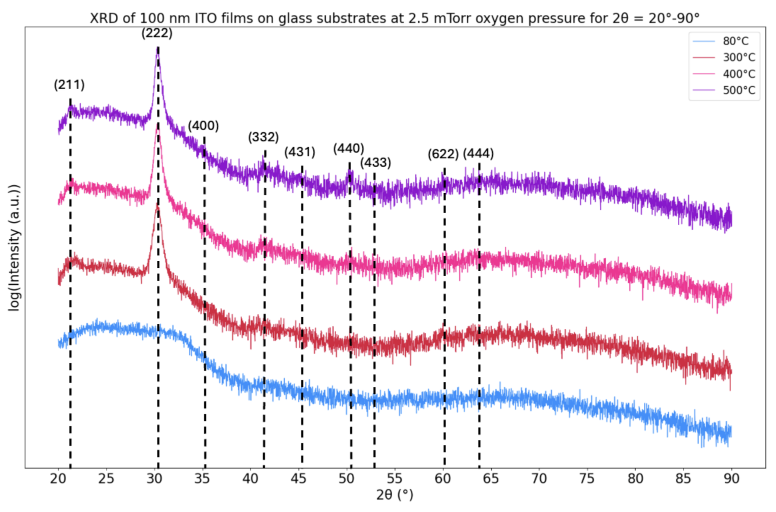
Contrary to expectations [5, 6], the **Sheet Resistivity** of the **ITO films** increased with temperature, possibly due to poor film **crystallinity**; nucleation growth can form many small grains, which increase the scattering of free electrons. Alternatively, a non-uniform film composition or surface over-oxidation would result in phase separations that increase resistivity.





Optical transmission data showed that the **ITO films** had good overall **optical properties**, as expected from literature [7]. There was degradation at longer wavelengths for the films deposited at lower temperatures.

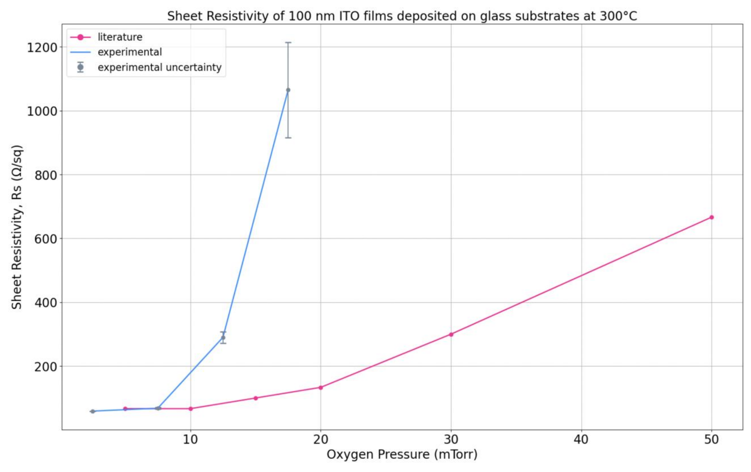
X-Ray Diffraction (XRD) indicated improving **crystallinity** at higher temperatures, as expected [8]. However, the overall **crystallinity** of all films was low as many expected peaks were absent; the 80°C sample is likely amorphous.



Atomic Force Microscopy (AFM) revealed smooth surfaces for three films, with **RMS roughness** values of 0.5 – 1.5 nm as expected [5, 9]. However, the 400°C film had an **RMS roughness** of 5.8 nm, which may explain the unexpected resistivity trend.

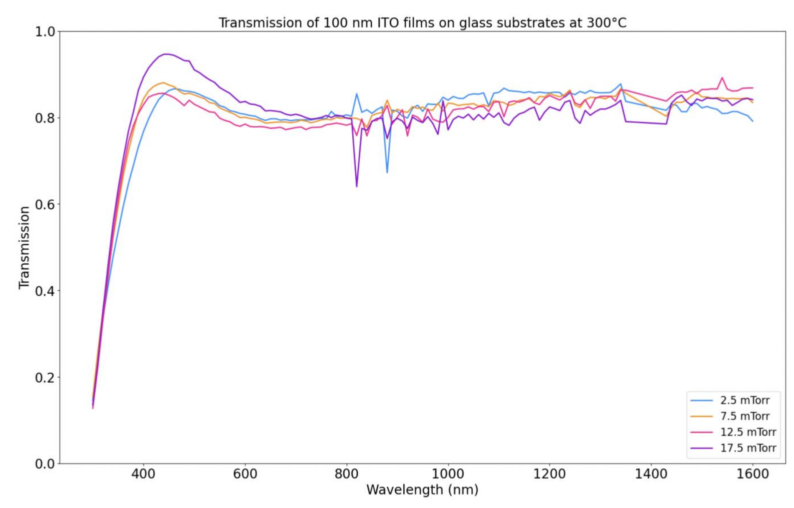
Research: Pressure Series

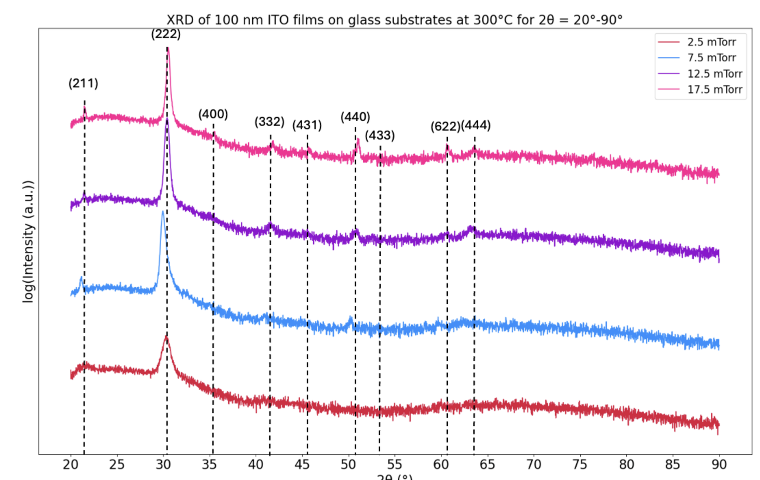
100 nm **ITO thin films** were deposited on glass substrates at oxygen pressures between 2.5 mTorr and 17.5 mTorr using **PLD** in a 300°C environment.



The **Sheet Resistivity** increased with oxygen pressure as expected [5], although at a quicker rate. This is likely due to the over-oxidation of tin, which reduces the number of available oxygen vacancies and thus free electrons in the lattice.

Optical transmission data indicated that the **ITO films** had good **optical properties**. However, the expected transmission increase with pressure [10] was not observed; further **ellipsometry** analysis is needed. Slight degradation at longer wavelengths is observed for the films deposited at lower pressures.





XRD showed improved **crystallinity** with pressure, as expected [8], although the peaks shifted to higher 2θ values suggesting a reduced lattice spacing due to over-oxidation.

AFM revealed smooth surfaces for the 2.5 and 17.5 mTorr films, with low **RMS roughness** values of 0.5 – 1.5 nm as expected [5, 9]. Higher **RMS roughness** values were seen for the 7.5 and 12.5 mTorr films (7.3 nm and 3.0 nm respectively), possibly due to contamination.

Conclusion

The project successfully fabricated and characterised **ITO thin films,** assessing their **optical** and **electrical properties** for integration into **PICs** and the capability for optical-to-electrical signal conversion.

While both film series exhibited good **optical properties** with high transmission plateaus, their **resistivities** differed from expected literature values.

Further **PLD** optimisation, including adjustments to the laser fluence and substrate (Si or SiN), is needed to address these anomalies. Additional characterisation using **ellipsometry** is recommended to determine the films' **optical constants**, whilst optical non-linear testing could evaluate **ITO's** usability with low-power illumination sources. Enhancement of the nonlinear **optical properties** may be achieved through doping (with zinc or aluminium) or using lithography to etch metamaterials.

References

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