Lab report: Transparent conductive oxides

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# Introduction

Transparent conductive oxides are an interesting material as it combines the properties of being electrically conductive and being able to transmit light. These properties give them a wide array of applications in cutting-edge electronic and optoelectronic devices. Examples of these are solar panels, OLED displays and touchscreens.

Metals, known for their high electrical conductivity, have a fundamental drawback—opacity. The opacity of metals arises from their ability to absorb and reflect light across the electromagnetic spectrum, preventing the transmission of visible light and rendering them unsuitable for transparent applications. In contrast, TCOs exhibit a remarkable property: simultaneous transparency and electrical conductivity. This seemingly paradoxical behaviour stems from the distinctive electronic structure of TCOs, allowing them to conduct electricity while permitting the passage of visible light.

This report will discuss both the specific electrical and optical properties for different TCO materials. It will also discuss the experimental procedure on how these measurements were taken.

# Materials and methods

## Thickness measurement

The thickness of a TCO is important to know both when designing the dimensions of a device as well as for calculating other properties down the line such as resistivity.

The thickness was measured using a stylus profiler. The model used in this report is the Alpha-step D-500. This device has a measurement range of a few nanometres to about 1200 micrometres. Both the operation and data collection are handled by software.

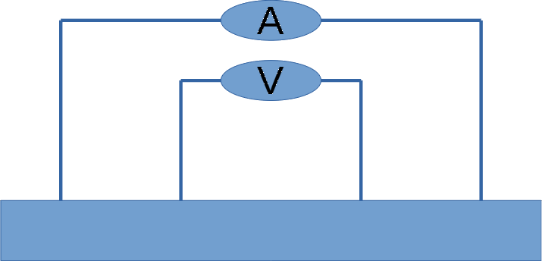
To measure the thickness of a TCO sample, first place the sample under the stylus in the machine and make sure it is in the general vicinity of the stylus. Next use the software to precisely put the stylus next to a transition point between the coated and the uncoated area. To take the measurement, engage the stylus and let the software perform the measurement. Afterwards normalise the acquired data and note in down.

Figure 1: four probe setup with amp meter and voltmeter

## Resistance measurement

The two types of resistance properties, the resistivity and the sheet resistance are important parameters to know for building applications involving the TCO.

The sheet resistance is measured using a four-probe method. Here a current is passed through the oxide using two probes. An additional two probes are put in between, and the voltage is measured. Using the following equation is subsequently used to calculate the sheet resistance: this results the value in Ω/square.

Following above measurements, the resistivity is easy to calculate using the following formula:

with Rs the sheet resistance and t the thickness.

## Carrier properties measurement

The electrical carrier has two properties: the type and the mobility. These can be measured using the hall effect. The measuring device used is the M91 FastHalltm measurement controller by Lakeshore Cryotronics.

The measurement is done using the Van der Pauw technique which allows the different Hall measurements to be done on a square sample with the edges as electrical connections. First the device measures the sheet resistance and with help from the first measurement the resistivity. It needs this to calculate the carrier type and mobility down the line. The other measurement it needs is the Hall coefficient. It calculates this by measuring the voltage under a constant current and a constant magnetic field, in this case 1T.

The carrier type is determined by the sign of the Hall coefficient. If it is positive (+) the type is P (holes), if it is negative (-) the type is N (electrons) [1]

The carrier mobility is calculated using the following formula: where RH is the Hall coefficient and e is the fundamental charge [1]

The carrier mobility is calculated with the hall coefficient and resistivity using the following equation

## Optical properties

The optical properties were measured using the PVE300 system, this system uses an integrating sphere to measure the reflectance and transmittance. The absorption can be calculated from these values.

To make the measurement light at different wavelengths into the device to get a result in function of this wavelength.

An integrating sphere is a spherical device which is completely reflective inside, meaning all the light entering the device will be reflected until it hits the detector. Integrating the detector value over time gives the total amount of light that entered the sphere.

The transmittance is measured by putting the device in front of the sphere and shining the light upon it. All the transmitted light will be absorbed by the sphere.

The reflectance is calculated by inserting the device on side of the sphere and letting the light shine in, so the reflected light gets captured by the sphere.

The absorption can be calculated by subtracting the transmittance and the reflectance from 100%.

# Results

The results achieved using the methods described above will be given here.

## Thickness

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| TCO | T1 (nm) | T2(nm) | T3(nm) | Total (nm) |
| ITO A | 162.38 | 150.85 | 132.52 | 148.58 |
| ITO B | 181.83 | 139.32 | 114.99 | 145.38 |
| ZnO | 1043.60 | 990.77 | 987.80 | 1007.39 |

The thickness is pretty straightforward, multiple measurements were taken to get an average.

## Resistance

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Rs1 (Ω) | Rs2 (Ω) | Rs3 (Ω) | Rs avg (Ω) | Resistivity\* (Ω) |
| ITO A | 0.669\*102 | 0.658\*102 | 0.740\*102 | 0.689\*102 | 4.637\*108 |
| ITO B | 0.430\*102 | 0.511\*102 | 0.444\*102 | 0.462\*102 | 3.178\*108 |

\*Assuming the ITOs are analogous to the ones in the thickness measurement

## Carrier

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Carrier concentration (1/cm2) | Carrier type | Mobility (cm2/V\*s) | Resistivity | Hall voltage |
| ITO A | 2.93905\*1015 ±39.2\*109 | n | 30.7725±400\*10-6 | 69.01Ω/sq  ±28.8µΩ/sq | -2.12173mV  ±21.4nV |
| ITO B | 5.15964\*1015 ±80.2\*109 | n | 28.6261±445\*10-6 | 42.26Ω/sq  ±53µΩ/sq | -1.20892mV  ±18.8nV |
| ITO A (80nm) | 367.419\*1018 ±2.93\*1015 | n | 30.7716±245\*10-6 | 552µΩ\*cm  ±472.4pΩ | -2.12176mV  ±16.9nV |
| ITO B (140nm) | 368.56\*1018 ±9.73\*1015 | n | 28.6319±756\*10-6 | 591.5µΩ\*cm  ±437.3pΩ | -1.20887mV  ±31.9nV |

## Optical

These are the complete tables for the transmittance (T), reflectance (R) and absorption (A) for each TCO material. Note around the shorter wavelengths, the measurement are a bit unstable due to calibration.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| ITO 1 | | | | | | | | | | |
| Wavelength (nm) | T (%) | | | Wavelength (nm) | R (%) | | | Wavelength | | A (%) |
| 300 | -32,4783 | | | 300 | 29,44705 | | | 300 | | 103,03128 |
| 310 | -1,9792 | | | 310 | 23,78178 | | | 310 | | 78,19742 |
| 320 | 19,2963 | | | 320 | 19,29342 | | | 320 | | 61,41028 |
| 330 | 24,03662 | | | 330 | 15,7302 | | | 330 | | 60,23318 |
| 340 | 39,41153 | | | 340 | 12,25268 | | | 340 | | 48,33579 |
| 350 | 47,73057 | | | 350 | 15,21564 | | | 350 | | 37,05379 |
| 360 | 55,69469 | | | 360 | 16,62929 | | | 360 | | 27,67602 |
| 370 | 60,1958 | | | 370 | 20,31476 | | | 370 | | 19,48944 |
| 380 | 62,49753 | | | 380 | 22,59169 | | | 380 | | 14,91078 |
| 390 | 64,44488 | | | 390 | 26,04359 | | | 390 | | 9,51153 |
| 400 | 66,48135 | | | 400 | 27,32435 | | | 400 | | 6,1943 |
| 410 | 68,82786 | | | 410 | 27,61792 | | | 410 | | 3,55422 |
| 420 | 70,45122 | | | 420 | 27,08444 | | | 420 | | 2,46434 |
| 430 | 72,48161 | | | 430 | 26,03905 | | | 430 | | 1,47934 |
| 440 | 74,31927 | | | 440 | 24,55147 | | | 440 | | 1,12926 |
| 450 | 76,32991 | | | 450 | 22,89295 | | | 450 | | 0,77714 |
| 460 | 78,46606 | | | 460 | 21,4301 | | | 460 | | 0,10384 |
| 470 | 80,15772 | | | 470 | 19,75742 | | | 470 | | 0,08486 |
| 480 | 81,52025 | | | 480 | 18,01921 | | | 480 | | 0,46054 |
| 490 | 83,05467 | | | 490 | 16,13206 | | | 490 | | 0,81327 |
| 500 | 84,76958 | | | 500 | 14,4914 | | | 500 | | 0,73902 |
| 510 | 86,13852 | | | 510 | 13,19682 | | | 510 | | 0,66466 |
| 520 | 87,12502 | | | 520 | 12,17503 | | | 520 | | 0,69995 |
| 530 | 88,03194 | | | 530 | 11,18028 | | | 530 | | 0,78778 |
| 540 | 88,48181 | | | 540 | 10,1914 | | | 540 | | 1,32679 |
| 550 | 88,92458 | | | 550 | 9,62176 | | | 550 | | 1,45366 |
| 560 | 89,11563 | | | 560 | 9,30259 | | | 560 | | 1,58178 |
| 570 | 89,46916 | | | 570 | 9,16097 | | | 570 | | 1,36987 |
| 580 | 89,42155 | | | 580 | 8,99348 | | | 580 | | 1,58497 |
| 590 | 89,26615 | | | 590 | 8,84716 | | | 590 | | 1,88669 |
| 600 | 88,97379 | | | 600 | 8,81938 | | | 600 | | 2,20683 |
| 610 | 88,7343 | | | 610 | 8,89793 | | | 610 | | 2,36777 |
| 620 | 88,37354 | | | 620 | 9,18618 | | | 620 | | 2,44028 |
| 630 | 87,97396 | | | 630 | 9,51931 | | | 630 | | 2,50673 |
| 640 | 87,48469 | | | 640 | 9,92196 | | | 640 | | 2,59335 |
| 650 | 87,1526 | | | 650 | 10,05333 | | | 650 | | 2,79407 |
| 660 | 86,72675 | | | 660 | 10,29039 | | | 660 | | 2,98286 |
| 670 | 86,34996 | | | 670 | 10,51402 | | | 670 | | 3,13602 |
| 680 | 86,13988 | | | 680 | 10,96332 | | | 680 | | 2,8968 |
| 690 | 85,90566 | | | 690 | 11,41843 | | | 690 | | 2,67591 |
| 700 | 85,63029 | | | 700 | 11,79672 | | | 700 | | 2,57299 |
| 710 | 85,12922 | | | 710 | 12,15822 | | | 710 | | 2,71256 |
| 720 | 84,87077 | | | 720 | 12,5668 | | | 720 | | 2,56243 |
| 730 | 84,19293 | | | 730 | 12,90736 | | | 730 | | 2,89971 |
| 740 | 83,99772 | | | 740 | 13,00637 | | | 740 | | 2,99591 |
| 750 | 83,66566 | | | 750 | 13,23619 | | | 750 | | 3,09815 |
| 760 | 83,27733 | | | 760 | 13,43669 | | | 760 | | 3,28598 |
| 770 | 82,68008 | | | 770 | 13,61907 | | | 770 | | 3,70085 |
| 780 | 82,48841 | | | 780 | 13,77687 | | | 780 | | 3,73472 |
| 790 | 82,32846 | | | 790 | 14,15051 | | | 790 | | 3,52103 |
| 800 | 82,0909 | | | 800 | 14,00101 | | | 800 | | 3,90809 |
| 810 | 81,60917 | | | 810 | 13,87003 | | | 810 | | 4,5208 |
| 820 | 81,22163 | | | 820 | 13,93307 | | | 820 | | 4,8453 |
| 830 | 81,19222 | | | 830 | 14,10537 | | | 830 | | 4,70241 |
| 840 | 81,52092 | | | 840 | 14,01726 | | | 840 | | 4,46182 |
| 850 | 81,3776 | | | 850 | 13,98574 | | | 850 | | 4,63666 |
| 860 | 80,98421 | | | 860 | 14,0985 | | | 860 | | 4,91729 |
| 870 | 80,78286 | | | 870 | 13,99684 | | | 870 | | 5,2203 |
| 880 | 80,79839 | | | 880 | 14,06939 | | | 880 | | 5,13222 |
| 890 | 80,72595 | | | 890 | 13,91927 | | | 890 | | 5,35478 |
| 900 | 80,62226 | | | 900 | 13,64256 | | | 900 | | 5,73518 |
| ITO 2 | | | | | | | | | | |
| Wavelength (nm) | T (%) | | | Wavelength (nm) | R (%) | | | Wavelength | | A (%) |
| 300 | 1,78045 | | | 300 | -12,2183 | | | 300 | | 110,43785 |
| 310 | 3,56706 | | | 310 | -5,32916 | | | 310 | | 101,7621 |
| 320 | 12,20188 | | | 320 | 0,08343 | | | 320 | | 87,71469 |
| 330 | 32,77344 | | | 330 | 6,87505 | | | 330 | | 60,35151 |
| 340 | 46,63482 | | | 340 | 5,22438 | | | 340 | | 48,1408 |
| 350 | 53,76433 | | | 350 | 1,12288 | | | 350 | | 45,11279 |
| 360 | 63,39436 | | | 360 | 3,80281 | | | 360 | | 32,80283 |
| 370 | 70,81339 | | | 370 | 7,7248 | | | 370 | | 21,46181 |
| 380 | 74,33319 | | | 380 | 9,12825 | | | 380 | | 16,53856 |
| 390 | 76,02393 | | | 390 | 10,76094 | | | 390 | | 13,21513 |
| 400 | 78,14929 | | | 400 | 12,16253 | | | 400 | | 9,68818 |
| 410 | 79,32927 | | | 410 | 14,13408 | | | 410 | | 6,53665 |
| 420 | 80,05776 | | | 420 | 15,60821 | | | 420 | | 4,33403 |
| 430 | 80,08746 | | | 430 | 16,87734 | | | 430 | | 3,0352 |
| 440 | 79,37125 | | | 440 | 17,74422 | | | 440 | | 2,88453 |
| 450 | 78,73142 | | | 450 | 18,48174 | | | 450 | | 2,78684 |
| 460 | 78,5954 | | | 460 | 19,39955 | | | 460 | | 2,00505 |
| 470 | 78,54284 | | | 470 | 20,08542 | | | 470 | | 1,37174 |
| 480 | 78,36891 | | | 480 | 20,56272 | | | 480 | | 1,06837 |
| 490 | 78,00376 | | | 490 | 20,95917 | | | 490 | | 1,03707 |
| 500 | 77,75124 | | | 500 | 21,33749 | | | 500 | | 0,91127 |
| 510 | 77,45973 | | | 510 | 21,74268 | | | 510 | | 0,79759 |
| 520 | 77,28872 | | | 520 | 21,91872 | | | 520 | | 0,79256 |
| 530 | 77,13703 | | | 530 | 22,15219 | | | 530 | | 0,71078 |
| 540 | 76,98271 | | | 540 | 22,25292 | | | 540 | | 0,76437 |
| 550 | 76,9284 | | | 550 | 22,35088 | | | 550 | | 0,72072 |
| 560 | 76,83832 | | | 560 | 22,15381 | | | 560 | | 1,00787 |
| 570 | 77,0019 | | | 570 | 22,11169 | | | 570 | | 0,88641 |
| 580 | 77,05635 | | | 580 | 22,09783 | | | 580 | | 0,84582 |
| 590 | 77,17121 | | | 590 | 22,0832 | | | 590 | | 0,74559 |
| 600 | 77,24087 | | | 600 | 21,87182 | | | 600 | | 0,88731 |
| 610 | 77,41696 | | | 610 | 21,57992 | | | 610 | | 1,00312 |
| 620 | 77,67184 | | | 620 | 21,2727 | | | 620 | | 1,05546 |
| 630 | 77,68345 | | | 630 | 21,08349 | | | 630 | | 1,23306 |
| 640 | 77,49959 | | | 640 | 20,85954 | | | 640 | | 1,64087 |
| 650 | 77,37292 | | | 650 | 20,53739 | | | 650 | | 2,08969 |
| 660 | 77,66106 | | | 660 | 20,32902 | | | 660 | | 2,00992 |
| 670 | 77,99012 | | | 670 | 19,91174 | | | 670 | | 2,09814 |
| 680 | 78,27849 | | | 680 | 19,4869 | | | 680 | | 2,23461 |
| 690 | 78,39764 | | | 690 | 19,06197 | | | 690 | | 2,54039 |
| 700 | 78,64534 | | | 700 | 18,85889 | | | 700 | | 2,49577 |
| 710 | 78,72034 | | | 710 | 18,27272 | | | 710 | | 3,00694 |
| 720 | 79,06073 | | | 720 | 17,93988 | | | 720 | | 2,99939 |
| 730 | 79,00371 | | | 730 | 17,83459 | | | 730 | | 3,1617 |
| 740 | 79,02877 | | | 740 | 17,69673 | | | 740 | | 3,2745 |
| 750 | 79,11613 | | | 750 | 17,33009 | | | 750 | | 3,55378 |
| 760 | 79,53219 | | | 760 | 16,95377 | | | 760 | | 3,51404 |
| 770 | 79,31566 | | | 770 | 16,65068 | | | 770 | | 4,03366 |
| 780 | 79,22499 | | | 780 | 16,01474 | | | 780 | | 4,76027 |
| 790 | 79,68189 | | | 790 | 15,7788 | | | 790 | | 4,53931 |
| 800 | 80,20465 | | | 800 | 15,5339 | | | 800 | | 4,26145 |
| 810 | 80,15064 | | | 810 | 15,12264 | | | 810 | | 4,72672 |
| 820 | 80,2453 | | | 820 | 14,69182 | | | 820 | | 5,06288 |
| 830 | 80,69451 | | | 830 | 14,58457 | | | 830 | | 4,72092 |
| 840 | 80,93248 | | | 840 | 14,09624 | | | 840 | | 4,97128 |
| 850 | 81,02976 | | | 850 | 13,59131 | | | 850 | | 5,37893 |
| 860 | 81,04814 | | | 860 | 13,34714 | | | 860 | | 5,60472 |
| 870 | 81,10409 | | | 870 | 13,20577 | | | 870 | | 5,69014 |
| 880 | 80,90323 | | | 880 | 12,88762 | | | 880 | | 6,20915 |
| 890 | 81,06268 | | | 890 | 12,59967 | | | 890 | | 6,33765 |
| 900 | 81,44608 | | | 900 | 12,35056 | | | 900 | | 6,20336 |
| ZnO | | | | | | | | | | | |
| Wavelength (nm) | | T (%) | Wavelength (nm) | | | R (%) | Wavelength | | A (%) | | |
| 300 | | -1,5625 | 300 | | | -17,08844 | 300 | | 118,6509 | | |
| 310 | | -7,96964 | 310 | | | -11,38947 | 310 | | 119,3591 | | |
| 320 | | -0,13141 | 320 | | | -4,38895 | 320 | | 104,5204 | | |
| 330 | | -2,24525 | 330 | | | 12,71469 | 330 | | 89,53056 | | |
| 340 | | -4,4686 | 340 | | | 13,93778 | 340 | | 90,53082 | | |
| 350 | | -3,01686 | 350 | | | 9,15519 | 350 | | 93,86167 | | |
| 360 | | -3,48718 | 360 | | | 13,30539 | 360 | | 90,18179 | | |
| 370 | | -0,34576 | 370 | | | 12,33721 | 370 | | 88,00855 | | |
| 380 | | 1,47314 | 380 | | | 15,15285 | 380 | | 83,37401 | | |
| 390 | | 23,25079 | 390 | | | 11,33262 | 390 | | 65,41659 | | |
| 400 | | 48,64432 | 400 | | | 17,8166 | 400 | | 33,53908 | | |
| 410 | | 66,75559 | 410 | | | 10,71136 | 410 | | 22,53305 | | |
| 420 | | 70,0676 | 420 | | | 21,49144 | 420 | | 8,44096 | | |
| 430 | | 75,18231 | 430 | | | 9,54037 | 430 | | 15,27732 | | |
| 440 | | 84,07464 | 440 | | | 15,58749 | 440 | | 0,33787 | | |
| 450 | | 77,23589 | 450 | | | 20,89247 | 450 | | 1,87164 | | |
| 460 | | 77,92213 | 460 | | | 12,37657 | 460 | | 9,7013 | | |
| 470 | | 86,61783 | 470 | | | 9,49657 | 470 | | 3,8856 | | |
| 480 | | 87,13308 | 480 | | | 17,16174 | 480 | | -4,29482 | | |
| 490 | | 80,89857 | 490 | | | 21,01826 | 490 | | -1,91683 | | |
| 500 | | 78,69846 | 500 | | | 15,73548 | 500 | | 5,56606 | | |
| 510 | | 83,71704 | 510 | | | 9,40858 | 510 | | 6,87438 | | |
| 520 | | 89,99482 | 520 | | | 10,0137 | 520 | | -0,00852 | | |
| 530 | | 89,36647 | 530 | | | 15,94265 | 530 | | -5,30912 | | |
| 540 | | 84,32515 | 540 | | | 19,76044 | 540 | | -4,08559 | | |
| 550 | | 79,92026 | 550 | | | 19,45711 | 550 | | 0,62263 | | |
| 560 | | 80,22965 | 560 | | | 14,70121 | 560 | | 5,06914 | | |
| 570 | | 84,48163 | 570 | | | 9,98622 | 570 | | 5,53215 | | |
| 580 | | 89,43007 | 580 | | | 8,59739 | 580 | | 1,97254 | | |
| 590 | | 91,16081 | 590 | | | 11,3717 | 590 | | -2,53251 | | |
| 600 | | 89,25768 | 600 | | | 15,84664 | 600 | | -5,10432 | | |
| 610 | | 85,16088 | 610 | | | 19,06527 | 610 | | -4,22615 | | |
| 620 | | 81,40702 | 620 | | | 19,90808 | 620 | | -1,3151 | | |
| 630 | | 79,73874 | 630 | | | 18,22757 | 630 | | 2,03369 | | |
| 640 | | 80,53356 | 640 | | | 14,77762 | 640 | | 4,68882 | | |
| 650 | | 83,45435 | 650 | | | 11,00069 | 650 | | 5,54496 | | |
| 660 | | 87,27722 | 660 | | | 8,39836 | 660 | | 4,32442 | | |
| 670 | | 89,94939 | 670 | | | 8,66734 | 670 | | 1,38327 | | |
| 680 | | 91,32696 | 680 | | | 9,78525 | 680 | | -1,11221 | | |
| 690 | | 90,56643 | 690 | | | 13,36712 | 690 | | -3,93355 | | |
| 700 | | 88,19541 | 700 | | | 16,31804 | 700 | | -4,51345 | | |
| 710 | | 85,04614 | 710 | | | 18,63104 | 710 | | -3,67718 | | |
| 720 | | 82,21139 | 720 | | | 19,38558 | 720 | | -1,59697 | | |
| 730 | | 80,09494 | 730 | | | 19,27117 | 730 | | 0,63389 | | |
| 740 | | 79,574 | 740 | | | 17,25912 | 740 | | 3,16688 | | |
| 750 | | 80,64877 | 750 | | | 14,98741 | 750 | | 4,36382 | | |
| 760 | | 82,35814 | 760 | | | 12,41383 | 760 | | 5,22803 | | |
| 770 | | 84,04308 | 770 | | | 9,61606 | 770 | | 6,34086 | | |
| 780 | | 86,90002 | 780 | | | 7,95089 | 780 | | 5,14909 | | |
| 790 | | 89,01421 | 790 | | | 6,85871 | 790 | | 4,12708 | | |
| 800 | | 89,99091 | 800 | | | 7,93197 | 800 | | 2,07712 | | |
| 810 | | 90,69444 | 810 | | | 8,73605 | 810 | | 0,56951 | | |
| 820 | | 89,42225 | 820 | | | 11,04188 | 820 | | -0,46413 | | |
| 830 | | 88,54954 | 830 | | | 13,2557 | 830 | | -1,80524 | | |
| 840 | | 86,32626 | 840 | | | 14,99871 | 840 | | -1,32497 | | |
| 850 | | 83,93237 | 850 | | | 16,93782 | 850 | | -0,87019 | | |
| 860 | | 82,10174 | 860 | | | 18,18987 | 860 | | -0,29161 | | |
| 870 | | 80,39681 | 870 | | | 18,9542 | 870 | | 0,64899 | | |
| 880 | | 78,94248 | 880 | | | 18,87077 | 880 | | 2,18675 | | |
| 890 | | 78,92529 | 890 | | | 18,18357 | 890 | | 2,89114 | | |
| 900 | | 79,06633 | 900 | | | 17,18474 | 900 | | 3,74893 | | |
| Etched ZnO | | | | | | | | | | | |
| Wavelength (nm) | | T (%) | Wavelength (nm) | | | R (%) | Wavelength | | A (%) | | |
| 300 | | -4,375 | 300 | | | -19,2699 | 300 | | 123,6449 | | |
| 310 | | -7,21063 | 310 | | | -13,3235 | 310 | | 120,5342 | | |
| 320 | | 6,438896 | 320 | | | -3,36486 | 320 | | 96,92597 | | |
| 330 | | -7,34024 | 330 | | | 5,815244 | 330 | | 101,525 | | |
| 340 | | -2,89855 | 340 | | | 0,834982 | 340 | | 102,0636 | | |
| 350 | | -4,03727 | 350 | | | 1,49565 | 350 | | 102,5416 | | |
| 360 | | -3,89744 | 360 | | | 3,593426 | 360 | | 100,304 | | |
| 370 | | -1,33366 | 370 | | | 3,769052 | 370 | | 97,56461 | | |
| 380 | | -0,31196 | 380 | | | 2,346681 | 380 | | 97,96528 | | |
| 390 | | 20 | 390 | | | 4,269386 | 390 | | 75,73061 | | |
| 400 | | 42,5695 | 400 | | | 7,296527 | 400 | | 50,13397 | | |
| 410 | | 54,38898 | 410 | | | 9,923401 | 410 | | 35,68761 | | |
| 420 | | 63,05877 | 420 | | | 11,76047 | 420 | | 25,18076 | | |
| 430 | | 67,96239 | 430 | | | 11,48079 | 430 | | 20,55682 | | |
| 440 | | 71,46887 | 440 | | | 11,90383 | 440 | | 16,6273 | | |
| 450 | | 74,54958 | 450 | | | 13,18105 | 450 | | 12,26937 | | |
| 460 | | 75,72886 | 460 | | | 13,21566 | 460 | | 11,05548 | | |
| 470 | | 77,27774 | 470 | | | 12,61042 | 470 | | 10,11184 | | |
| 480 | | 78,69697 | 480 | | | 11,83135 | 480 | | 9,471681 | | |
| 490 | | 80,38877 | 490 | | | 11,55426 | 490 | | 8,056972 | | |
| 500 | | 80,69655 | 500 | | | 11,48462 | 500 | | 7,818831 | | |
| 510 | | 81,05049 | 510 | | | 12,22721 | 510 | | 6,722297 | | |
| 520 | | 81,86706 | 520 | | | 11,72204 | 520 | | 6,410907 | | |
| 530 | | 82,16085 | 530 | | | 10,9637 | 530 | | 6,87545 | | |
| 540 | | 83,16507 | 540 | | | 9,900803 | 540 | | 6,93413 | | |
| 550 | | 83,59958 | 550 | | | 9,488063 | 550 | | 6,912355 | | |
| 560 | | 84,15821 | 560 | | | 9,917562 | 560 | | 5,924232 | | |
| 570 | | 83,56247 | 570 | | | 10,80893 | 570 | | 5,628601 | | |
| 580 | | 83,58791 | 580 | | | 11,1644 | 580 | | 5,247697 | | |
| 590 | | 83,63237 | 590 | | | 11,2964 | 590 | | 5,071227 | | |
| 600 | | 83,30391 | 600 | | | 10,53886 | 600 | | 6,157235 | | |
| 610 | | 84,07556 | 610 | | | 9,504438 | 610 | | 6,419999 | | |
| 620 | | 84,57111 | 620 | | | 8,588282 | 620 | | 6,840605 | | |
| 630 | | 85,30295 | 630 | | | 7,399595 | 630 | | 7,297459 | | |
| 640 | | 85,13071 | 640 | | | 6,746605 | 640 | | 8,122686 | | |
| 650 | | 85,25795 | 650 | | | 7,077733 | 650 | | 7,664318 | | |
| 660 | | 85,7065 | 660 | | | 7,615388 | 660 | | 6,678111 | | |
| 670 | | 85,14434 | 670 | | | 8,266637 | 670 | | 6,589024 | | |
| 680 | | 85,22631 | 680 | | | 8,913392 | 680 | | 5,860294 | | |
| 690 | | 85,49025 | 690 | | | 9,738169 | 690 | | 4,771581 | | |
| 700 | | 84,79103 | 700 | | | 10,29112 | 700 | | 4,917843 | | |
| 710 | | 84,99042 | 710 | | | 10,16445 | 710 | | 4,84513 | | |
| 720 | | 85,75568 | 720 | | | 9,733908 | 720 | | 4,510412 | | |
| 730 | | 85,574 | 730 | | | 9,133048 | 730 | | 5,292956 | | |
| 740 | | 85,50843 | 740 | | | 7,751539 | 740 | | 6,740033 | | |
| 750 | | 86,55339 | 750 | | | 7,429105 | 750 | | 6,017506 | | |
| 760 | | 86,52665 | 760 | | | 6,100188 | 760 | | 7,373167 | | |
| 770 | | 85,7731 | 770 | | | 5,182658 | 770 | | 9,04424 | | |
| 780 | | 86,44498 | 780 | | | 5,287018 | 780 | | 8,268003 | | |
| 790 | | 86,20358 | 790 | | | 4,853142 | 790 | | 8,943282 | | |
| 800 | | 85,62479 | 800 | | | 5,296865 | 800 | | 9,078344 | | |
| 810 | | 86,02177 | 810 | | | 5,329543 | 810 | | 8,648685 | | |
| 820 | | 85,02203 | 820 | | | 6,002346 | 820 | | 8,975627 | | |
| 830 | | 85,4954 | 830 | | | 6,361416 | 830 | | 8,143186 | | |
| 840 | | 84,97614 | 840 | | | 7,384986 | 840 | | 7,63887 | | |
| 850 | | 84,71845 | 850 | | | 8,172828 | 850 | | 7,108726 | | |
| 860 | | 84,47055 | 860 | | | 8,663691 | 860 | | 6,865755 | | |
| 870 | | 84,19473 | 870 | | | 9,127166 | 870 | | 6,678101 | | |
| 880 | | 84,60596 | 880 | | | 10,05818 | 880 | | 5,335856 | | |
| 890 | | 84,73432 | 890 | | | 10,15903 | 890 | | 5,106649 | | |
| 900 | | 85,08097 | 900 | | | 9,790178 | 900 | | 5,128856 | | |

Figure : plots of all the data

# Conclusion

In conclusion, this report delves into the properties of transparent conductive oxides (TCOs), emphasizing their unique combination of electrical conductivity and light transmittance. TCOs, unlike metals, manage to conduct electricity while allowing visible light passage, making them invaluable in various cutting-edge applications such as solar panels, OLED displays, and touchscreens.

The experimental focus involved measuring electrical and optical properties of different TCO materials. Thickness measurements using the Alpha-step D-500 stylus profiler provided crucial data for designing devices and calculating properties like resistivity. The four-probe method determined sheet resistance, enabling the calculation of resistivity, while the Hall effect technique measured carrier properties like type and mobility.

Optical properties were explored using the PVE300 system, with an integrating sphere for measuring reflectance and transmittance. The results, as outlined in the provided tables, offered insights into the behaviour of ITO and ZnO at varying wavelengths.

The key findings include variations in thickness, resistance, carrier properties, and optical characteristics among the TCO materials tested. The plots in Figure 2 visually represent the collected data.

In summary, this study contributes valuable insights into TCOs, shedding light on their diverse properties and showcasing their potential for advancing technologies in the electronic and optoelectronic realms.