

# Thermally stable ultra thin metal transparent electrodes

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**Abstract** - *Transparent electrodes made of ultra thin metal films are highly competitive with respect to Transparent Conductive Oxides, e.g. ITO. We report on thermally stable nickel transparent electrodes.*

## Introduction

Wide band gap semiconductors with heavy doping have been widely investigated as transparent electrodes. They are known as Transparent Conductive Oxides (TCOs) with Indium Tin Oxide (ITO) probably the most used of them. The trade-off between low electrical resistivity and high optical transmittance that can be achieved in TCOs has led to their use in many electro-optic devices such as solar cells, photo-detectors and Organic Light Emitting Diodes (OLEDs)[1]. TCOs deposition is, however, far from being a straightforward process. The influences of oxygen pressure, substrate temperature or post-deposition treatments on electrical resistivity and optical transparency of the film have been widely studied and regarded as potential drawbacks.

We have shown in previous works that Ultra Thin Metal Films (UTMFs) can possess higher electrical conductivity than TCOs while still having similar optical transparency [2, 3]. In addition, they can be grown through a single step deposition process, such as ultra high vacuum sputtering. In this paper we investigate the temperature stability of nickel-based UTMFs. We show that the electrical resistivity of films with thicknesses  $\geq 3$  nm does not change significantly for annealing temperatures  $\leq 90^\circ\text{C}$ . Also, in the case of film thickness  $\geq 5$  nm, the electrical resistivity does not change significantly for temperatures up to  $145^\circ\text{C}$ .

## Experimental results

Ultra thin nickel films were sputtered onto glass substrates at room temperature using a *Kenosistec Dual Chamber* DC sputtering machine in a pure argon (Ar) atmosphere. We used 8 mTorr Ar pressure and 200 W DC Power. Resulting deposition rate was  $1.6 \text{ \AA/s}$ . Fig.1(a) and Fig.1(b) show respectively AFM images of blank BK7 substrate and a 3.4 nm Ni film taken five weeks after deposition with a *Digital Instrument D3100* AFM and associated software *WsXM* [4]. Surface roughness has to be kept below the thickness of the layer, otherwise films could be discontinuous and thus non-conductive. In our case, 3.4 nm film's RMS roughness is measured to be 0.36 nm using the *WsXM* software.

The electrical measurements were carried on using a *Cascade Microtech 44/7S 2791* four point probe connected to a *Keithley 2001* multimeter while a *Cary 500 Fourier Transform scan spectrometer* was used for optical transmittance measurements.

Five weeks after deposition UTMFs show electrical resistivity and optical transparency levels similar to ITO as shown in Fig.2(a) and Fig.2(b) respectively but slightly larger

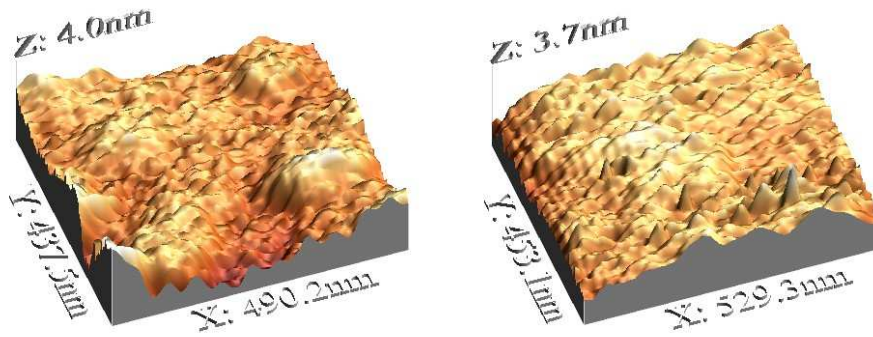


Figure 1: AFM images: (a) Blank BK7 substrate with a surface RMS roughness of 0.56 nm (b) 3.4 nm Ni film with a RMS roughness of 0.36 nm. Surface roughness levels of the substrate lower than deposited thickness are required for continuous films.

electrical resistivity when compared to previous works [2, 3] where it was measured straight after deposition. The difference is attributed to the advance in the oxidation process of the films. Note that the substrate's absorption is taken into account in the optical transmittance measurements as  $T_f = T_t/T_s$  where  $T_t$  is the total optical transmittance (film and substrate),  $T_f$  and  $T_s$  are the film's and substrate's optical transmittance respectively.

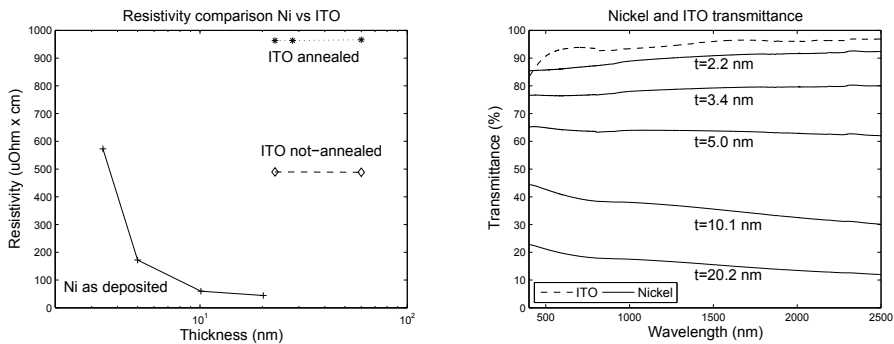


Figure 2: Comparison between UTMFs and ITO: (a) Electrical resistivity of ultra thin Ni films (solid line) 5 weeks after deposition. ITO annealed (dotted line) and non-annealed (dashed line) films are given as TCO reference. (b) Ultra thin Ni films (solid line) and ITO (dashed line) optical transmittance in the 400-2500 nm range. Two nanometer Ni film shows approximately the same optical transparency as ITO layers. The measurements were obtained five weeks after deposition.

The cumulative annealing treatments described in Table 1 were performed inside a *Selecta Hightemp 2001406* oven and temperature was measured using a *Fluke thermometer 52 II*

Treatment name	Time	Temperature°C
H1	2h	90
H2	2h 45 min	105
H3	2h 30 min	112
H4	2h 30 min	145
H5	2h 30 min	90
H6	X	-40 to 85

Table 1: Time and temperature of the annealing treatments applied to the nickel films. These treatments were performed cumulatively. Treatment H6 corresponds to temperature cycles ranging from -40 to 85°C at 1.4°C per second.

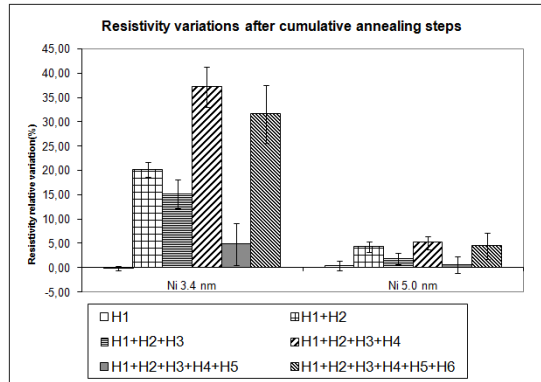


Figure 3: Electrical resistivity variation after cumulative annealing treatment.

thermometer and 80 PK-1 thermocouple. The first annealing treatment - labeled as H1 - was performed five weeks after the films had been deposited.

Electrical resistivity variations were measured after each annealing step on the same samples of different thicknesses. The values reported in Fig.3 are an average among 6 measurements. The formation of a natural oxide film due to oxygen indiffusion reduces the effective metallic layer, thus leading to higher electrical resistivity as shown in Fig.3, this effect being more significant for thinner films. Electrical resistivity variations of layers thicker than 5.0 nm are found to remain within 5% for all the annealing treatments whereas thinner films show larger variations. Accordingly, Fig.3 presents only the relative electrical resistivity variations for 3.4 nm and 5.0 nm films. Harder conditions, i.e. higher temperature, lead to larger electrical resistivity variations. The effect upon the 5.0 nm film is significantly reduced, with all variations within 6% meaning thus this film maintains similar conductivity along all the annealing process. In addition, also for films if 3.4 nm the variations are negligible below 90°C.

## Conclusions

Ultra thin Ni films have been deposited using ultra high vacuum sputtering on glass substrates. The deposited films show continuity despite their very small thickness. The observed temperature stability together with the optical transmittance and electrical resistivity performances confirm that Ultra Thin Metal Films are serious competitors to Transparent Conductive Oxides, such as ITO, for those applications where transparent electrodes are required.

## Acknowledgements

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