

Study and Characterization of Indium Oxynitride Photoconductors

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Received: June 9, 2013; Revised: November 7, 2013

Multifunctional materials are a new class of thin films and coatings. These materials show interesting characteristics for application in many scientific areas, in special electronic and photonic technologies. These characteristics include sensitivity for thermal, light, mechanical, chemical and other influences, high resistivity, high electrical isolation and transparency in visible range. Recently it was obtained a new oxide type that combines oxygen, nitrogen and indium: the indium oxynitride. In this work, we study the deposition of indium oxynitride by reactive sputtering for application in photoconductor sensors. The deposition processes were performed in a home build magnetron sputtering system, using a four-inch pure In target, nitrogen and oxygen as process gases. The pressure was kept constant at 10 mtorr and the RF power (13.56 MHz) was constant at 250 W. The photoconductors were made with these thin films. The photoelectric detectors were analyzed by IxV (current versus voltage) analyses. The IxV analysis presented a low leakage current (10^{-8} A). The photoelectric effect was observed from the difference between the case with emitted light and dark currents. It increased around 140 times, under illumination of a halogen lamp. The Hall Effect measurements indicated that the films were n-type semiconductors. The increase in the oxygen concentration added in the plasma, promoted the change in the character of these thin films from conductor to semiconductor material.

Keywords: *indium oxynitride, optoelectronic and photonic sensors, photo detectors, thin film sensors*

1. Introduction

The area of optoelectronics has seen substantial progress in recent years. Especially with the discovery of new materials that can be used as light sensors. Indium oxynitride (InNO) can be considered as a new material with properties between semiconductor indium nitride (InN) and insulator indium oxide (In_2O_3)^[1,2].

InNO is a semitransparent material of pale yellow color and has a wide band gap in the range 3.4-3.6 eV (nearest indium oxide), which makes it an excellent candidate to be employed in photo sensors in the ultraviolet region. Furthermore, it can be used as material for solar cells fabrication³. This ternary alloy belongs to a new class of materials with optical, mechanical and electrical properties which are potentially interesting for industrial applications⁴. Numerous properties of the InNO, such as the refractive index and the photoelectric effect intensity, vary according to the proportion of oxygen and nitrogen contained in the formed film.

In this work we study the deposition of indium oxynitride by reactive sputtering for application in photoconductor sensors. The photoelectric detectors can be divided into three classes: the photoconductors, photovoltaic and photo emitters. The photoconductive and photovoltaic detectors are directly based on semiconductors in which photons are

absorbed by the semiconductor material, producing electron-hole pairs, which are separated by an electric field. These detectors use the photoelectric effect (internal), where the photon energy is high enough to carry the electrons to the conduction band of the semiconductor material.

The photoconductor on the other hand, is essentially a resistor sensitive to radiation, consisting of two ohmic contacts. A photon with energy $h\nu$, higher than the band gap energy is absorbed to produce an electron-hole pair, consequently changing the electrical conductivity of the semiconductor. In most cases, the change in conductivity is measured through electrodes fixed on the semiconductor surface. For a material with low resistance, the photoconductor is normally operated in a constant current circuit mode. Examples are the photoconductors made of GaAs, GaN and AlGaIn junctions.

2. Materials and Methods

2.1. Deposition process

In this work, silicon wafers with resistivity in the range of 10-20 Ohm cm, three inch diameter, 280 mm thick, p-type, (100) were used.

Initially, a cleaning process ($4\text{H}_2\text{SO}_4 + 1\text{H}_2\text{O}_2$) followed by HF dipping (2%), was performed. The deposition of

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the indium oxynitride films was performed in magnetron sputtering system using an indium pure target. Five series of thin films were deposited with oxygen (10%, 20%, 50%, 80% and 85%) and nitrogen.

2.2. Hall effect measurements

This technique enables one to obtain the values of charge density, resistivity, sheet resistance, mobility and carrier type (n-type or p-type). The measurements in this study were made at the Instituto de Física da Universidade de São Paulo with equipment from MMR technologies (Hall Van de Pauw Controller H50).

2.3. I-V measurements

In this work, we manufactured light-sensitive ohmic photoconductors using aluminum as the metal contact deposited on the InNO thin film (Figure 1). The potential difference is applied on the two aluminum contacts (0.5 cm diameter) and the halogen lamp light was focused in the film between them. In the photoconductor fabrication, aluminum circle contacts were deposited at the front side of the wafer by evaporation in order to obtain 300 nm thick layer. At the backside of the wafer, a 500 nm thick aluminum film was evaporated. Measurements were made with and without the presence of light from the halogen lamp.

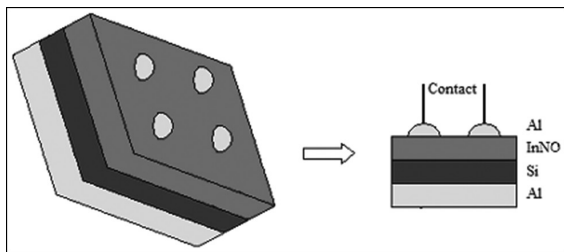


Figure 1. Design of photoconductor used in this study.

Table 1. Hall effect measurements.

Sample	Resistivity (Ω cm)	Type
10% O ₂	1.05×10^{-2}	N
20% O ₂	0.52	N
50% O ₂	0.76	N
80% O ₂	3.02×10^2	N
85% O ₂	4.76×10^4	N

Table 2. Electrical measurement (I-V).

Sample	Light current (A)	Dark current (A)	Increasing (times)	Position (V/cm)
10% O ₂	1.37×10^{-5}	1.12×10^{-7}	122.4	5.5×10^5
20% O ₂	5.23×10^{-6}	3.74×10^{-8}	139.8	5.5×10^5
50% O ₂	3.20×10^{-6}	9.31×10^{-8}	34.4	5.5×10^5
80% O ₂	7.89×10^{-7}	5.10×10^{-8}	15.5	5.5×10^5
85% O ₂	3.82×10^{-7}	2.64×10^{-8}	14.5	5.5×10^5

3. Results and Discussion

The electrical measurements were carried out at the Instituto de Física da USP with a MMR technologies (Hall Van de Pauw Controller H50) equipment, in room temperature.

The results obtained from the Hall effect measurements (Table 1) show in general that the resistivity of the InNO films deposited on Si is very high (using InN values as reference: 1.6 to 4 mW.cm^[3]). It can be associated with the photoconductor IxV analysis that shows a low leakage current (Tables 2 and 3).

The indium nitride is an n-type semiconductor due to the high amount of defects in its structure^{4,5}. When an alloy as the indium oxynitride is deposited, some nitrogen bonds are eventually replaced by oxygen. The defects remain and the semiconductor remains n-type.

When oxygen is added, the resistivity increases gradually. Indium nitride thin films are semiconductors that are closest to conductive materials due to its low resistivity, a value equivalent to $3 \times 10^{-3} \Omega$ cm^[6,7].

It is evident that the InNO deposited with 10% oxygen has resistivity ($1.1 \times 10^{-2} \Omega$ cm) closer to InN. In other hand, the InNO deposited with 85% oxygen has a much higher resistivity ($4.8 \times 10^4 \Omega$ cm), approaching of the InO resistivity, which is an insulator.

The intensity of the photoelectric effect was observed from the difference of case with light on and dark current values. The results are shown in Figure 2 to Figure 6.

All manufactured devices were analyzed. It was verified that the photoconductor that showed notable results in terms of electrical measurement (IxV) and photoelectric effect was the one deposited with InNO thin film, with oxygen concentration of 20% and 250 W RF power on p-type silicon substrate. The added oxygen forms the indium oxynitride thin film and establishes links with metallic indium, thereby decreasing the carrier concentration and leakage current (dark current), which promotes the increase of the photoelectric effect⁸. However, high concentrations of oxygen decrease conductivity and sensor sensitivity.

On Table 2, it can be observed that this sample was the one with the lowest dark current, indicating low leakage current (3.74×10^{-8} A). In addition to this fact, the observed photoelectric effect intensity is the biggest for among all the samples (increased 139.8 times).

In Table 3 we present the results of light and dark currents in the presence of negative electric field. With these data it was verified that the graphs are in fact symmetric, which indicates an ohmic behavior.

Table 3. Electrical measurement (I-V).

Sample	Light current (A)	Dark current (A)	Increasing (times)	Position (V/cm)
10% O ₂	1.22×10^{-5}	1.20×10^{-7}	101.7	-5.5×10^5
20% O ₂	3.87×10^{-6}	3.86×10^{-8}	100.3	-5.5×10^5
50% O ₂	2.45×10^{-6}	8.15×10^{-8}	30.1	-5.5×10^5
80% O ₂	1.02×10^{-6}	2.96×10^{-8}	34.5	-5.5×10^5
85% O ₂	5.00×10^{-7}	4.22×10^{-8}	11.9	-5.5×10^5

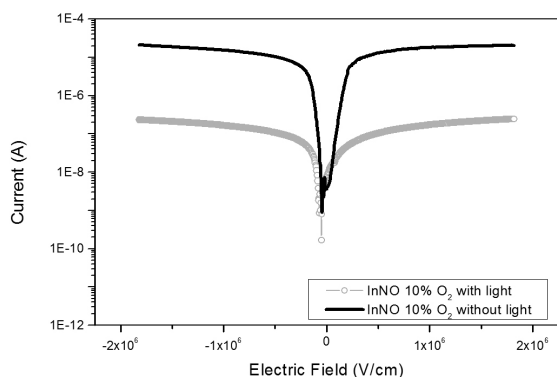


Figure 2. Current as a function of Electric Field for InNO 10% O₂ with light and without light.

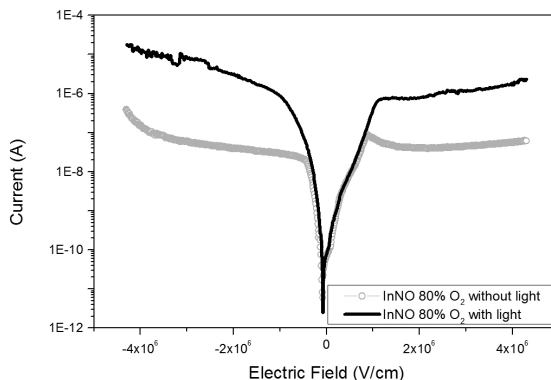


Figure 5. Current as a function of Electric Field for InNO 80% O₂ with light and without light.

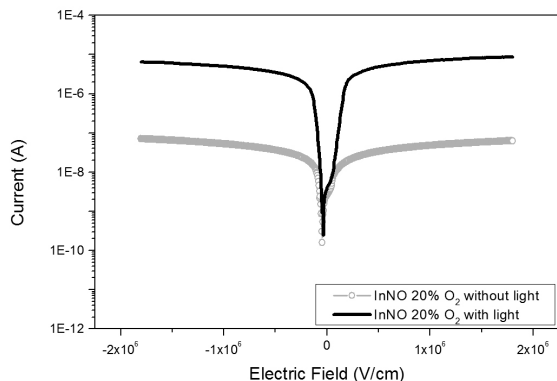


Figure 3. Current as a function of Electric Field for InNO 20% O₂ with light and without light.

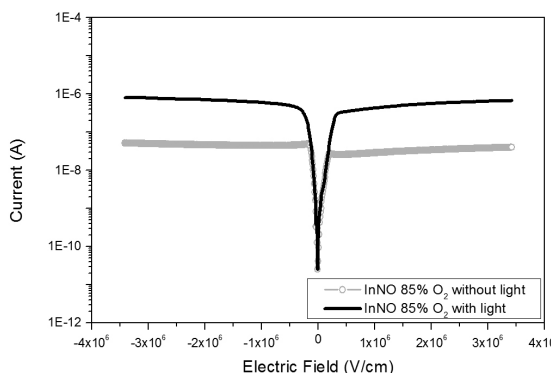


Figure 6. Current as a function of Electric Field for InNO 85% O₂ with light and without light.

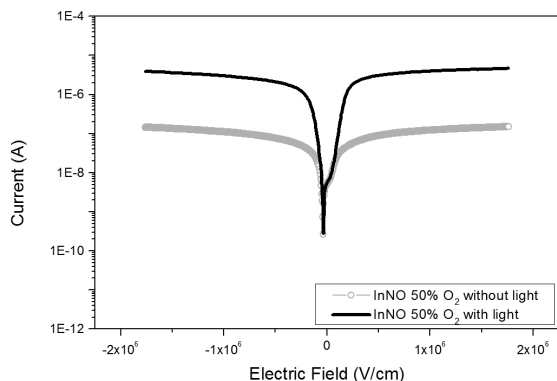


Figure 4. Current as a function of Electric Field for InNO 50% O₂ with light and without light.

The fact is that the aluminum acts as an ohmic contact in these samples. Therefore, it is being used as part of the sensors.

Incorporation of oxygen to the film reduces the conductivity and, therefore, material defects. Addition of oxygen facilitates the formation of indium oxynitride thin film, thereby decreasing the carrier concentration and leakage current, eventually enhancing the photoelectric effect in low concentrations of this element in deposition process of thin film.

With these satisfactory results, it is possible to use such devices in many areas. These sensors may be used, for example, as photosensor for aerosol detection, after been calibrated with the assistance of a pyranometer. It can also still be used in biomedical and optical sensors.

4. Conclusions

The films produced with the addition of different concentrations of oxygen form the indium oxynitride, a ternary alloy with promising characteristics for application in the microelectronics area. These films showed photoelectric effect with high intensities, especially the thin film deposited with InNO 20% oxygen.

There are evidences that the incorporation of oxygen to the film reduces the conductivity, which may mean that there was a reduction of defects in that material. The added oxygen forms the indium oxynitride thin film and establishes links with metallic indium, thereby decreasing the carrier

concentration and leakage current (dark current), which promotes the increase of the photoelectric effect. However, high concentrations of oxygen decrease conductivity and sensor sensitivity.

Acknowledgments

The authors would like to thank to the Laboratório de Sistemas Integráveis and Instituto de Física da Universidade de São Paulo for the measurements, to Mr. Nelson Ordenez for technical support and Fapesp, CNPq for financial support.

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