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High Performance Schottky Photodiode Based on Polycrystalline ITO Deposited at Room Temperature

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ABSTRACT

An indium tin oxide/hydrogenated amorphous silicon (ITO/a-Si:H) Schottky photodiode based on room temperature deposition of optically transparent polycrystalline ITO is reported in this paper. The photodiode exhibits low leakage current (7×10^{-10} A/cm^2) when biased at −2 V. Secondary ion mass spectroscopy (SIMS) measurements indicate that this notable improvement in device characteristics stems from reduced diffusion of oxygen, rather than indium, from the ITO into the a-Si:H layer, thus preserving the integrity of the Schottky interface.

I. Introduction

ITO is widely used in solar cells, flat panel displays, and image sensors [1]. However, its transparency and electrical conductivity are key considerations with respect to device quality. In image sensor applications, we need an ITO film that is polycrystalline to ensure transparency and chemical stability. Polycrystalline ITO can be achieved at deposition temperatures above 150 °C, but when used in Schottky diodes, the high deposition temperature results in diffusion of indium and oxygen into the a-Si:H layer, thereby degrading device performance [2]. Thus the deposition of ITO at non-elevated temperatures is crucial. But at these temperatures, the deposited films tend to be amorphous in structure with very weak crystallinity [3]. One method to increase crystallinity of the ITO is to introduce O_2 [4] or H_2O [5] in the sputtering gas. However, because of partial pressure considerations, control of film resistivity is very limited, leading to a narrow process tolerance [6]. Additionally, the presence of O_2 or H_2O leads to formation of positively charged states at the Schottky interface [7]. These states act as trapping sites for photogenerated electrons and holes, thus giving rise to a significant increase in leakage current.

In this work, rather than using O_2 or H_2O, the optically transparent ITO in our Schottky photodiode was achieved through sputter deposition of the material in pure argon at room temperature [8]. The device is characterized in terms of the leakage current. The interface integrity is characterized in terms of the diffusion profiles for oxygen and indium by SIMS measurements, to gain insight into the mechanisms underlying leakage current.

II. Experiments

The fabrication process of the Schottky photodiode is fully compatible with the a-Si:H thin film transistor technology. We start with a 120 nm Cr layer which acts as the bottom electrode, followed by deposition of a highly doped n^+a-Si:H layer (thickness 50 nm) for ohmic contact. Thick (1 μm) intrinsic a–Si:H is then deposited to serve as the active layer, with rf power density of 10 mW/cm^2, temperature of 260 °C, chamber pressure of 250 mtorr, and SiH_4 flow rate of 50 sccm. For all devices, the a–Si:H is etched in buffered HF to remove any surface oxide before the samples were loaded into the sputtering system. Polycrystalline ITO (thickness 80 nm) is then deposited in pure argon at room temperature for the Schottky contact layer and light window. The target-substrate distance was 15 cm and the substrate temperature associated with heating by the plasma is measured to be less than 40 °C. The deposition conditions are listed in Table I. The film resistivity is below 6×10^{-4} Ω-cm and its variation over a large number of samples was less than 5%. Optical transmittance of the film, within the range of visible wavelengths, is in excess of 80% (Fig. 1). X-ray diffraction measurements (Fig. 2) show a strong presence of the <222> peak, which confirms that the films are polycrystalline in structure. The metallization layer is sputtered Al (thickness 1 μm). For purposes of comparing device characteristics, some photodiodes were annealed at 260 °C for 12 hours. The device schematic and operating principle are illustrated in Fig. 3 along with its cross-section taken by scanning electron microscopy (SEM) in Fig. 4.

Optical transmittance measurements were carried out with the ITO deposited on 7059 Corning glass substrates, using an ORIEL optical system whose wavelength lies in the visible spectrum ranging from 400 nm to 900 nm. The X-ray diffraction (XRD) measurements were taken with a Nicolet-12 diffractometer (Cu radiation, 30 kV, and 20 mA).

III. Results and discussions

A low leakage current is required to minimize background signal and to achieve high dynamic range. A comparison of the leakage current characteristics of the photodiode (area 300×300 μm^2) for different processing conditions is depicted in Fig. 5. At a bias voltage of –2 V, the leakage current associated with the room temperature ITO is about 1 pA. In contrast, the leakage current for the 260 °C ITO is higher by a factor of 2. At high reverse voltages, the leakage current increases rapidly for the annealed samples; here, the difference in leakage current at -3.5 V is about one order of magnitude.

Contributions to the leakage current in Schottky photodiodes stem from thermionic emission, interface tunnelling, bulk thermal generation, and edge effects. The barrier height in Schottky photodiodes is smaller

TABLE I
Sputter deposition parameters of polycrystalline indium tin oxide.

Base pressure	2×10^{-6} torr
Process pressure	20 mtorr
rf power	300 W
Substrate temperature	Non-heat
Substrate-sample distance	15 cm
Substrate rotation	10 rpm

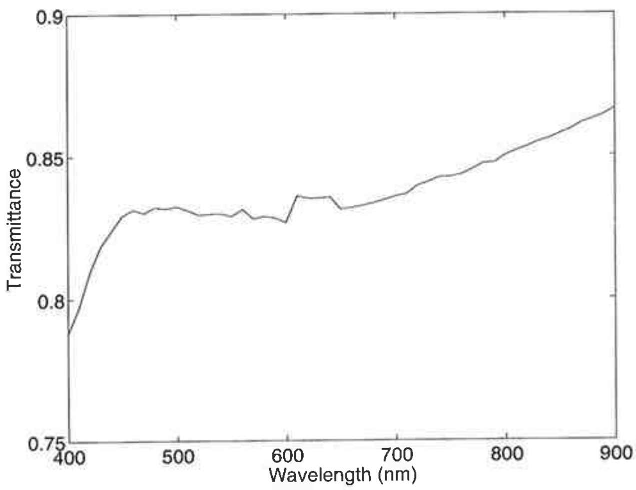

Fig. 1. Transmittance spectrum of ITO deposited at room temperature.

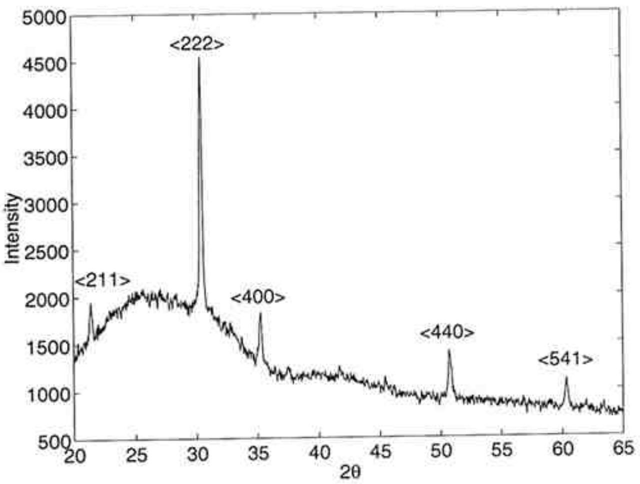

Fig. 2. XRD pattern of ITO deposited at room temperature.

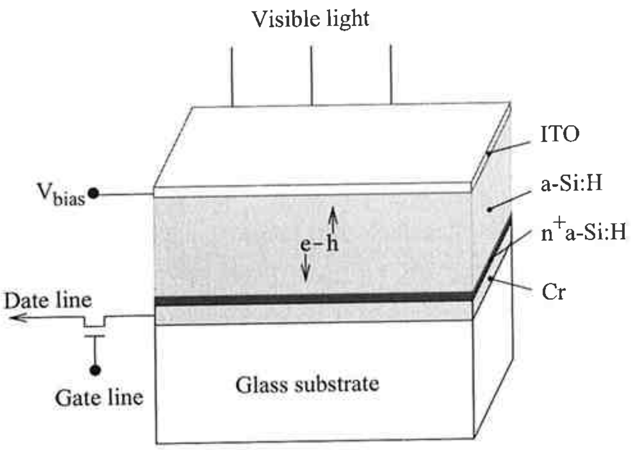

Fig. 3. Schematic of ITO/a-Si:H Schottky photodiode.

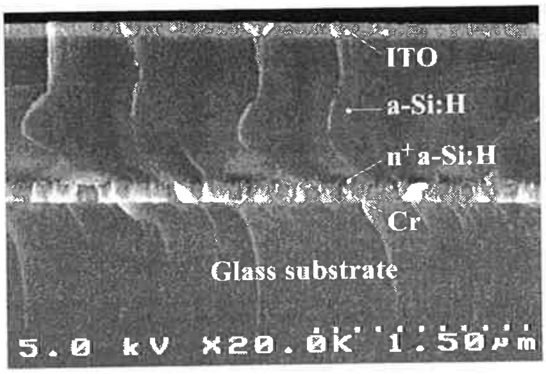

Fig. 4. SEM photodiode cross-section.

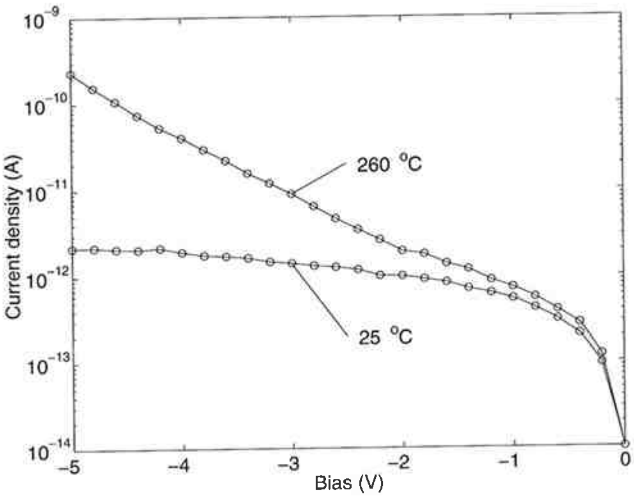

Fig. 5. Photodiode leakage current for ITO deposited at room temperature (no annealing) and subject to annealing at 260 °C.

compared to the *pin* counterpart, and therefore its leakage current is intrinsically higher. Bulk thermal generation is a feature of the active layer and it is generally small in comparison. Edge effects are relatively insignificant in small photodiode areas. The tunnelling component depends on interface integrity. In ITO/a–Si:H Schottky diodes, the possible interaction of oxygen and indium with a–Si:H during ITO deposition introduces a high density of interface states. This in turn increases tunnelling and hence the leakage current. To gain insight into the variation in leakage current, SIMS measurements were performed to determine the distribution of oxygen and indium in the a–Si:H layer. Here, the thickness of ITO is 80 nm. It is observed that oxygen and indium diffuse into the a–Si:H by about 50 nm and 150 nm, respectively, at room temperature (see Table II). In contrast, the corresponding diffusion depths of oxygen and indium, if the device is annealed at 260 °C, are about 53 and 176 nm, respectively. Here, the change in the indium is very small ($\sim$3 nm) while the change associated with oxygen is much larger ($\sim$26 nm). Therefore, the increase in leakage current can be attributed to the enhanced diffusion of oxygen rather than indium, if the device is annealed at high temperature (260 °C). Here, positively charged defect states in the bulk a–Si:H layer near the interface are created, which actively participate in tunnelling. At high bias voltages, the rapid increase in leakage current is due to band bending which results in increased interface states. Another observation is that there is no big difference in the diffusion depth for indium and oxygen in the a-Si:H layer, between the as-deposited samples and the samples annealed at 150 °C. Therefore, samples can be annealed at about 150 °C, if needed, to recover from light-soaked conditions.

TABLE II

DIFFUSION RANGE OF INDIUM AND OXYGEN IN A–SI:H (THICKNESS: 80 NM).

	Indium (nm)	Oxygen (nm)
25 °C	80 to 130	82 to 231
150 °C	81 to 131	83 to 236
260 °C	82 to 135	84 to 260

IV. CONCLUSIONS

ITO/a–Si:H Schottky photodiodes have been fabricated using polycrystalline ITO deposited at room temperature, which feature low leakage current (7×10^{-10} A/cm^2 at -2 V). When the device is annealed at 260 °C, the leakage current increases significantly. Here, the diffusion of oxygen, as opposed to indium, is identified to be the main cause for the increased leakage current. The detector demonstrated here extends the applications of a-Si:H technology to both optical imaging (e.g., in document scanning) and X-ray imaging. In particular, with the latter, the low-temperature ITO process reported here enables simple co-integration of the scintillating (phosphor) layer for enhanced X-ray conversion efficiency.

V. ACKNOWLEDGMENTS

This work is supported by the DALSA/NSERC Industrial Research Chair Program, the Communication and Information Technology Ontario (CITO), and the Natural Sciences and Engineering Research Council (NSERC) of Canada.

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