Advancements in Solution Processable Devices using Metal Oxides For Printed Internet-of-Things Objects

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Abstract

Internet-of-things (IoT) objects are expected to exceed 75 billion objects by 2020, and a large part of the expansion is expected to be at a finer granularity than existing silicon-based IoT objects (i.e. tablets and cell phones) can deliver [1]. Currently, placing a room light or a thermostat on the internet for remote control is considered progressive. However, if printed electronics can achieve performance increases, then IoT objects could be affixed to almost anything, such as coffee creamer cartons, cereal boxes, or that missing sock. Each of these IoT objects could be driving a sensor, perhaps position, temperature or pressure, essentially a multitude of applications. In order for IoT objects to emulate a simple postage stamp, with self-powering from energy scavenging and local energy storage, all housed in a non-toxic flexible form factor, advances in solution processable devices need to occur.

(Keywords: IoT, energy scavenging, low-power electronics, ALD, NDR, tunnel diodes, Manufacturing, CMOS and SOI)

Introduction

This talk will highlight advances by this collaborative international team in (1) metal oxide rectifying diodes for RF energy harvesting; (2) metal oxide tunnel barriers deposited by atomic layer deposition for negative differential resistance (NDR) devices using post-deposition annealing and novel precursors; and (3) metal oxide channel thin film transistors (TFT) with high mobilities and low operating voltages.

A. Solution Processed In_2O_3 Diodes

One modality for energy scavenging is the generation of DC power from absorbed RF energy germinated from sources like WiFi networks. Solution processed and organic diodes have shown promise in RFID, energy harvesting, and voltage multiplication applications [2]. Many of these rectifying diodes are based upon printed Schottky diodes. High-frequency air-stable solution processed rectifying diodes based on indium oxides have been successfully fabricated. The diodes have a vertical structure of Al-In_2O_3-Au fabricated on an SiO_2 coated Si wafer. The diodes offer excellent frequency performance. For an ac input voltage with an amplitude of 10 V, the dc output of a half-wave rectifier stays at 7 V up to at least 50MHz. The cutoff frequency of the diodes has reached 400MHz, entering ultra-high frequency (UHF) range. This is an excellent candidate for RF energy harvesting.

B. Low-Temperature Annealing of ALD Oxides

Post-deposition annealing studies on metal oxides deposited by atomic layer deposition (ALD) were conducted using conventional ALD precursors at low deposition temperatures, but above the temperature for organometallic precursor pyrolysis. By carefully shifting the energy level within the metal-oxide bandgap of localized defect states created by oxygen vacancies in the ALD tunneling barrier, a higher peak-to-valley current ratio (PVCR) and lower onset tunneling voltage is expected in our polymer tunnel diodes (PTD) [3-4]. MOS and PTD devices on silicon and ITO coated glass were annealed with varying ultraviolet (UV) and laser irradiation parameters, Fig. 1. UV and laser irradiation have shown to improve the reliability of the film morphology, composition, and leakage current of metal oxides [5-6].

C. Solution Processable In_2O_3 TFTs

Low voltage operation and low processing temperature of transistors with metal oxide channels remains a challenge. Commonly metal oxide transistors are fabricated at very high processing temperatures (above 500ºC) and their operation is not suitable for low power devices [7-8]. Here, thin film transistors (TFT) are reported based upon solution processable indium oxide (In_2O_3) for channel materials and room temperature processed anodized high-κ aluminum oxide (Al_2O_3) for gate dielectrics. Anodization empowers the room temperature deposition of dielectric, bypassing high temperature, high vacuum processes, with the added advantages of nanoscale deposition and denser oxide layers that mitigate leakage current [9-10].

Results and Discussion

Spectroscopic ellipsometry and XRD measurements were used to observe variations in the optical dielectric functions and structural properties of the irradiated oxide samples. Room temperature I-V and C-V (Fig. 2) characteristics of the PTDs and MOS structures are analyzed and the impact of UV and laser annealing on device performance, dielectric properties, and trap states will be reported.

The In_2O_3 TFTs shown in Fig. 3 operate well below V_{ds} of 3.0 V, with on/off ratio 10^5, subthreshold swing (S) 160 mV/dec, and low threshold voltage V_{th} 0.6 V. The electron mobility (μ) was found to be as high as 3.53 cm^2/Vs in the saturation regime and transconductance g_m 53 μS. Fig. 4 and 5 show the C-V measurements and low leakage gate current in the TFTs. Additionally, the interface trap density (D_{it}) in

the oxide/semiconductor interface was quite low i.e. 1.7×10^{12} cm^{-2} eV^{-1}, indicating good compatibility of In_2O_3 with anodic Al_2O_3.

With this report, we have shown advancements in metal-oxide based active devices that are synthesized by solution processing and low-temperature processing to realize the candidate discrete devices that will go into a complete printed IoT system.

Acknowledgments

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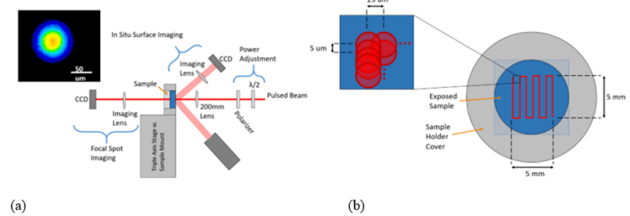

Fig. 1: (a) Experimental setup used for Laser Irradiation. (b) Raster of sample with triple-axis stage.

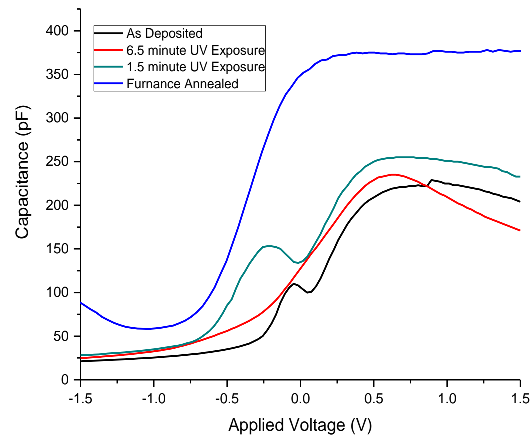

Fig. 2: Impact of UV annealing on the C-V characteristics of $Al/Ta_2O_5/Si$ structures.

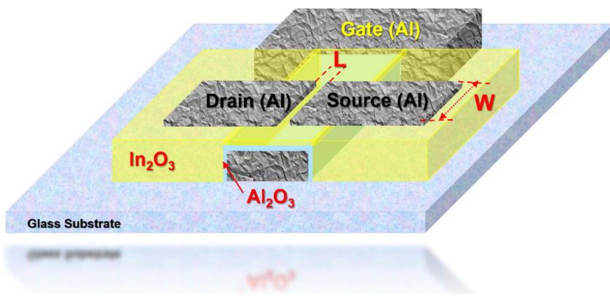

Fig. 3: Schematic structure of the In_2O_3 TFT with Al2O3 gate dielectric.

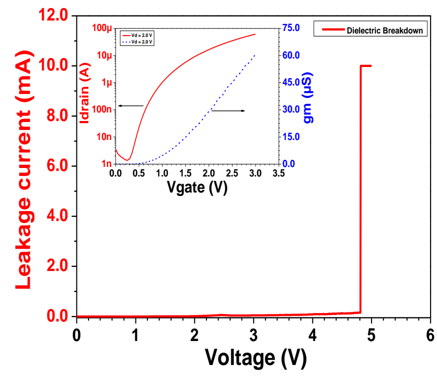

Fig. 5: Gate leakage current of In_2O_3 TFT.

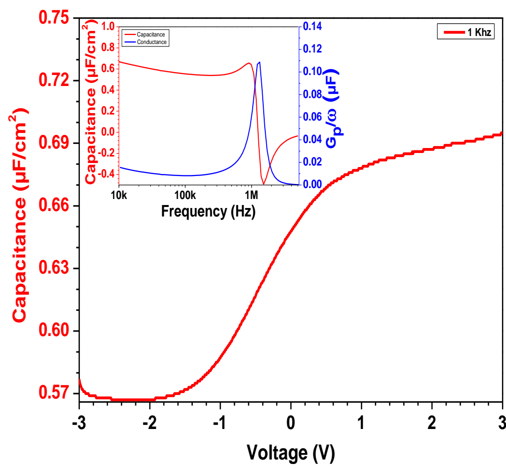

Fig. 4: C-V measurement of the In_2O_3 TFT.