Stretchable Gas and UV Sensors towards Wearable Electronics

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ABSTRACT

A distinctive microtectonic effect enabled oxygen deficient, nanopatterned zinc oxide (ZnO) thin films on an elastomeric substrate are introduced to realize large area, stretchable, transparent, and ultraportable sensors. The unique surface structures are exploited to create stretchable gas and ultraviolet light sensors, both of which outperform their rigid counterparts under room temperature conditions.

Keywords: stretchable electronics, wearable devices, sensors, gas, UV

1 INTRODUCTION

Metal oxides, often processed at high temperatures, are attractive candidates as the functional materials for a variety of such electronic and optoelectronic applications [1,2]. Their electronic properties can range from insulating to semiconducting and can be readily tuned by morphological and stoichiometric alterations. Combining these versatile oxide materials with flexible substrates will satisfy the demand for stretchable high performance devices.

The most common challenge faced is the incorporation of different materials which require different processing conditions. Widely used substrate materials such as polydimethylsiloxane (PDMS) can withstand only low processing temperatures (<100 °C) but are highly conformal (being elastomeric), while the yellow-brown tinted polyimide can withstand up to ~400 °C but offers low flexibility (due to its plasticity). Almost all high-performance functional oxides need to be crystalline and are deposited at high temperatures (ranging from 400 to 700 °C). They are also notorious for their brittle nature. These aspects have been bottlenecks in realising high performance, functional, flexible devices.

2 TRANSFER PROCESS

We have developed a ubiquitous transfer process which relies on the poor adhesion of platinum to silicon and allows multilayer structures to be defined, and peeled-off using PDMS [3]. This process has been successfully demonstrated using transparent indium tin oxide and zinc oxide thin films (both deposited at high temperatures) with stretchability of up to 15% which is exceptionally high for a brittle oxide. This process, depicted in Fig. 1, allows the creation of transparent stretchable electronics with nanometre resolution as well as large-area functional devices without the need of tailoring the production process to the design [4]. An overlapping plate-like thin film microstructure contributes to the enhanced strain performance; where this unique microstructure offers specific advantages that complement thin film electrodes.

The micro-tectonic phenomenon governs the stretchability of the thin oxide films [Fig. 2]. This phenomena occurs when the transferred brittle oxide layer forms micrometre-sized plates which overlap and slide over each other (similar to tectonic plates). Due to the high adhesion to the elastomer, an electrical contact is maintained between individual plates which combine to form one large functional surface.

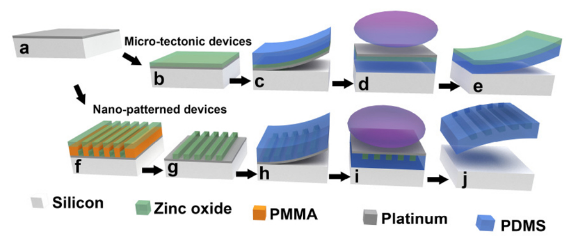

Figure 1: Realisation of oxide based, transparent, stretchable devices. Approach for fabrication of micro-tectonic nano-patterned devices is schematically depicted, where oxide materials are processed (with patterning and high temperature processes) on a weakly adhered platinum thin film. This platinum thin film enables a transfer process to realise oxide-based stretchable devices. Reproduced with permission from [4]

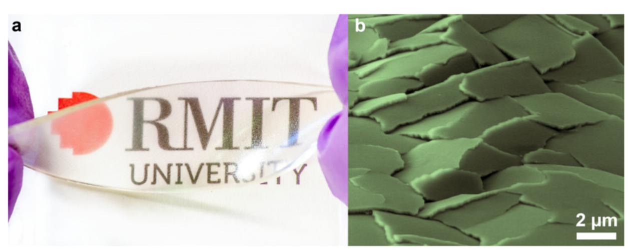

Figure 2: a) Transparency and the ability to flex and twist a microtectonic ZnO device is shown in this photograph. b) False-colour scanning electron image of the surface-cracked

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microtectonic surface of ZnO. Reproduced with permission from [4]

3 ROOM TEMPERATURE GAS SENSORS

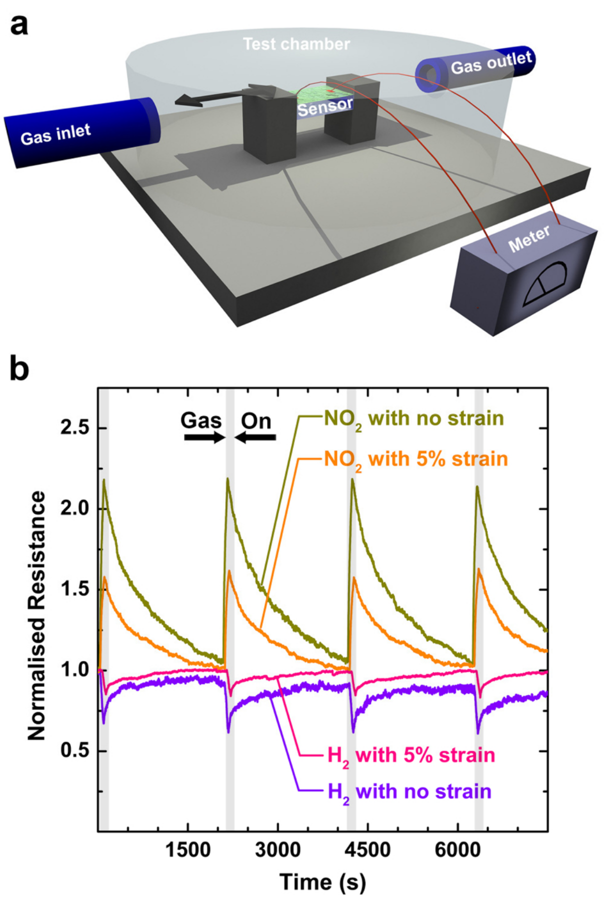

Figure 3: Testing of the ZnO gas sensors: a) Schematic representation of a sample during test in a chamber with controlled gas flow and *in situ* resistance measurement. b) Room temperature response of the microtectonic sensor to hydrogen and nitrogen dioxide in relaxed and stretched states (gray/shaded areas represent gas exposure for 80 s). Reproduced with permission from [4]

Oxygen-deficient ZnO films with a microtectonic surface morphology were defined with electrode pairs and operated as conductometric sensors [4]. The oxygen-deficient nature of the ZnO allows for higher adsorption of the test gases (hydrogen and nitrogen dioxide) which directly translates to superior sensitivity. The electrical resistance characteristics of the strained and unstrained microtectonic ZnO/PDMS sensor were acquired *in situ* under sequential exposure to zero air, hydrogen, and nitrogen dioxide [Fig. 3]. The stretchable gas sensors on PDMS were benchmarked against their rigid analogues fabricated on silicon. It is seen that the microtectonic sensor shows a higher sensitivity (>20%) and a significantly faster response than the rigid analogue [4]. This is attributed to an enhanced surface area due to the microtectonic morphology which enables larger number of gas molecules to interact with the ZnO surface and also the gas permeable nature of PDMS which further maximizes the exposed area by allowing the diffusion of gas molecules.

4 STRETCHABLE UV SENSORS

The photosensitive nature of ZnO can be utilised for detecting UV radiation. The dynamic response of resistance of the sensor subject to cyclic exposures of UV light is depicted in Fig. 4. Upon exposure to UV light, the resistance of the device decreases. The oxygen-deficient nature of the ZnO films used in this study attracts ambient oxygen, resulting in its adsorption on to the oxide surface. The electrical conduction decreases when oxygen is absorbed from ambient air, resulting in the formation of a depletion layer on the ZnO surface (OFF state). When exposed to UV light, the photogenerated carriers driven by the resulting electric field move to the surface, where they neutralize the absorbed oxygen leaving behind unpaired electrons which result in the increased conductivity (ON state). The microtectonic morphology of the ZnO provides a larger surface area for the oxygen adsorption, and hence, a greater proportion of unpaired carriers. This effect results in enhanced OFF/ON ratios seen in our devices.

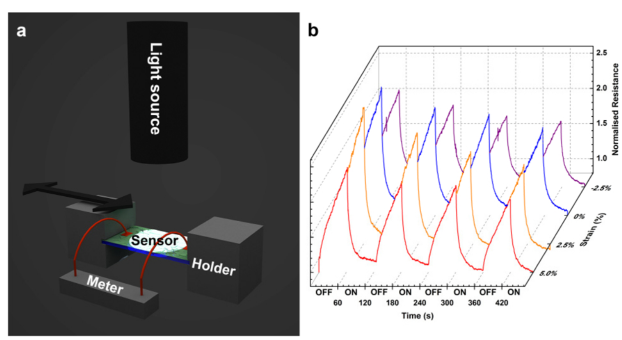

Figure 4: Optical sensing response of microtectonic ZnO to ultraviolet radiation. a) Schematic of testing arrangement with high energy UV illumination and microscale stretching capability for *in situ* measurements. b) Normalized resistance under cyclic exposure to darkness (OFF state) and broadband UV illumination of 1 sun (ON state) for different levels of uniaxial strain. Reproduced with permission from [4]

5 CONCLUSIONS

Stretchable and transparent gas and UV sensors are demonstrated using oxygen-deficient ZnO. The sensors show a high sensitivity to flammable and toxic gases as well as radiation in the UV-A and UV-B band. We demonstrate full functionality at room temperature under strain as well as an increased sensitivity through micro-tectonic surfaces by comparison to their rigid counterparts. Such transparent, stretchable ZnO devices offer significant potential for the development of cost-effective, biocompatible, and curvilinear electronic devices towards wearable technologies.

REFERENCES

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