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Towards metal chalcogenide nanowire-based colour-sensitive photodetectors

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ABSTRACT

In recent years, nanowires have been shown to exhibit high photosensitivities, and, therefore are of interest in a variety of optoelectronic applications, for example, colour-sensitive photodetectors. In this study, we fabricated two-terminal PbS, In_2S_3, CdS and ZnSe single-nanowire photoresistor devices and tested applicability of these materials under the same conditions for colour-sensitive (405 nm, 532 nm and 660 nm) light detection. Nanowires were grown via atmospheric pressure chemical vapour transport method, their structure and morphology were characterized by scanning and transmission electron microscopy (SEM and TEM), X-ray diffraction (XRD), and optical properties were investigated with photoluminescence (PL) measurements. Single-nanowire photoresistors were fabricated via *in situ* nanomanipulations inside SEM, using focused ion beam (FIB) cutting and electron-beam-assisted platinum welding; their current-voltage characteristics and photoresponse values were measured. Applicability of the tested nanowire materials for colour-sensitive light detection is discussed.

1. Introduction

Colour-sensitive photodetectors are desirable for a large variety of applications, for instance, in optical communications, digital imaging and environmental monitoring [1–4]. In recent years, nanowires (NWs) have been demonstrated to be superior to their bulk counterparts as photodetector materials mainly due to their higher sensitivities, which arise from the NW high surface area/volume ratio resulting in high density of surface states that act as trap sites for photogenerated holes, therefore increasing electron lifetime and enhancing the photocurrent [5,6]. Semiconducting chalcogenide materials with direct bandgap and large absorption coefficients, such as PbS, In_2S_3, CdS, ZnSe, are great candidates for next-generation NW-based light detectors due to their excellent photodetection properties [6–9]. Typical photodetectors can detect only a specific spectral band, therefore are not suitable for multi-colour detection with spectral selectivity. There are two general approaches of making colour-sensitive detectors: using broad-spectrum materials and wavelength-selective filters, or combining several materials with different bandgaps, including material doping and composition tuning. Using broad-spectrum photodetector materials combined with absorptive colour filters is a possibility; however, it involves additional fabrication steps and, to obtain highest efficiency, one would prefer light to be converted to photocurrent rather than reflected or absorbed in the filter layer. Research has been done on compositionally tuneable NWs and doping of NWs for wavelength-selective light detection [10,11], but there is a difficulty to extend the optical band outside the visible light range. Furthermore, it has been demonstrated that colour imaging is possible by varying the radius of silicon NWs to control spectral sensitivities [12]. However, a versatile strategy to obtain spectral selectivity is to select arbitrary photosensitive material NWs with different bandgaps, and incorporate them in a composite thin film or on an insulating substrate. Liu et al. demonstrated a method of incorporating photosensitive CdS, CdSeS and CdSe NWs into an amorphous indium zinc oxide thin film to obtain a transparent thin-film-transistor array, showing that such concept could be possibly used to fabricate multi-colour photodetectors [13]. Sang et al. utilized CdS, SnO_2, ZnO and Ga_2O_3 one-dimensional nanostructures to demonstrate colour-sensitive photodetection by simultaneously integrating them into an insulating substrate with a two-terminal device structure [14]. In such a way, the cut-off wavelengths of the selected semiconductor NW materials, defined by the bandgap, will determine the spectral selectivity. This approach benefits from substantial freedom to choose NW materials with desirable spectral band and high

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photoresponse. Furthermore, large-scale printing of NWs at defined locations on flexible substrates via roll-to-roll transfer has been demonstrated [15], thus enabling the development of NW based all-printed electronic and optoelectronic devices at low cost and with high performance.

In this work, we synthesised PbS, In_2S_3, CdS and ZnSe NWs and fabricated single-nanowire two-terminal photoresistor devices to test the applicability of these materials for colour-sensitive (red, green and blue light) photodetector applications, if they would be simultaneously incorporated on the same substrate. It is important to note that all these devices were prepared using the same method and tested under the same conditions. The measured NW photodetector properties were compared and analysed.

2. Experimental details

2.1. Nanowire synthesis and characterization

The following material NWs were synthesised via atmospheric pressure chemical vapour transport method in a horizontal quartz tube reactor by adjusting previously reported growth parameters: PbS [16], In_2S_3 [17], CdS [18], and ZnSe [19]. In all the cases, the NWs were grown on oxidized silicon wafers Si(110)/SiO_2 (*Semiconductor Wafer, Inc.*) coated with spherical Au nanoparticles used as a catalyst (*Smart materials*, water suspension, 50 nm diameter).

PbS NWs: 0.25 g $PbCl_2$ powder (*98%, Sigma Aldrich*) was loaded in a ceramic boat and placed in the centre of the quartz tube at 650 °C, Au/Si substrate was placed downstream in a lower temperature region. Excessive amount of sulphur powder (*enola SIA*) was placed upstream at 250 °C to create sulphur-rich atmosphere, while N_2 was used as a carrier gas. The temperature was kept constant for 20 min, followed by natural cooling to room temperature.

In_2S_3 NWs: Mixture of 0.5 g In and 0.5 g $InCl_3$ (*98%, Sigma-Aldrich*) powders were used as a source material and sent to the centre of the quartz tube. Au/Si substrate and sulphur powder were placed downstream and upstream, respectively, as in the previous case. Ar/H_2 (5%) gas mixture was used as a vapour carrier. The furnace was heated to 800 °C, temperature was held constant for

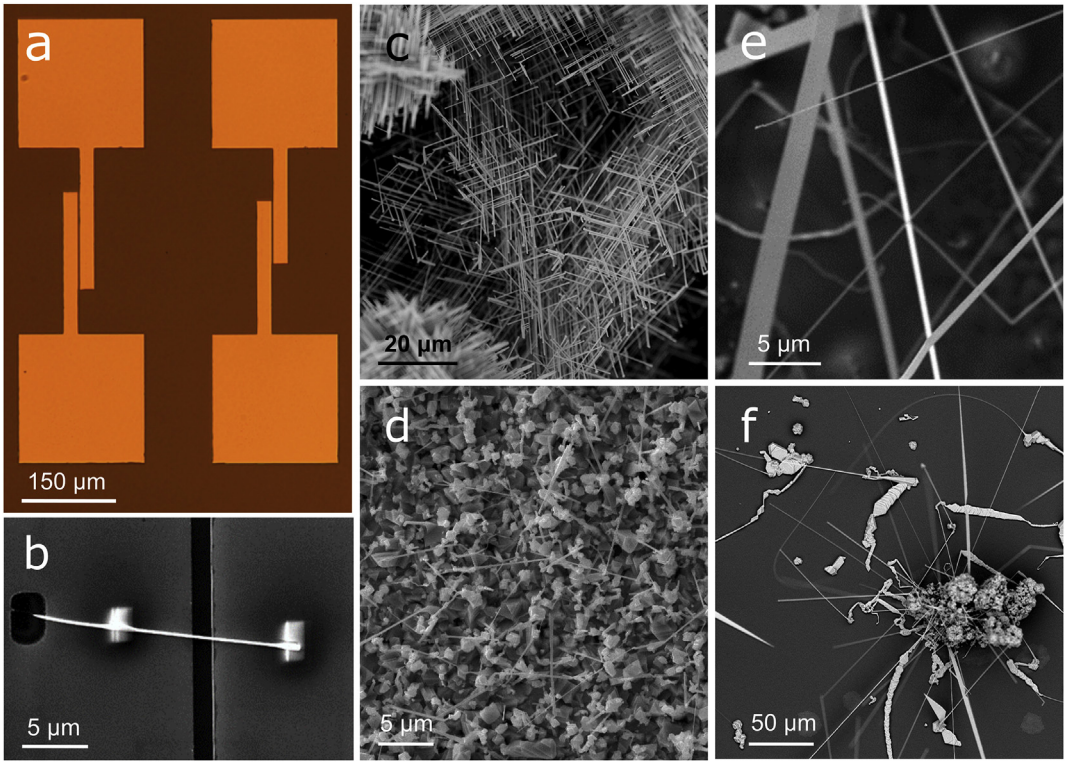

Fig. 1. (a) Optical microscope image of gold microelectrodes on the oxidized silicon substrate; SEM images of (b) a typical as-prepared nanowire photoresistor; as-grown (c) PbS, (d) In_2S_3, (e) CdS and (f) ZnSe nanowires.

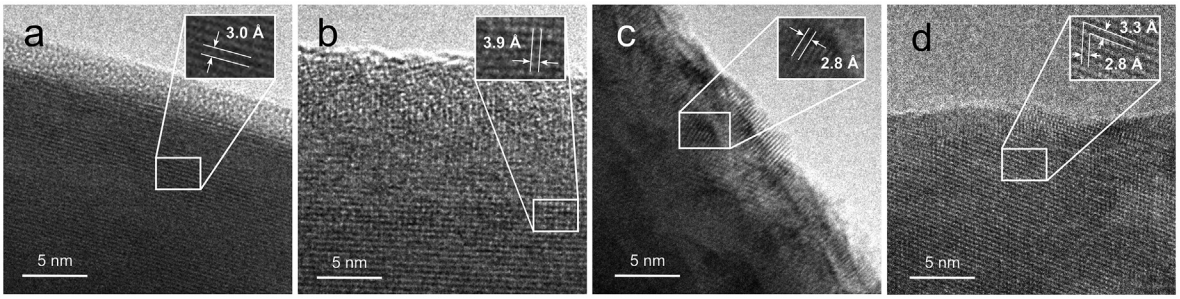

Fig. 2. TEM images of (a) PbS, (b) In_2S_3, (c) CdS and (d) ZnSe nanowires. Insets show measured atomic interlayer distances.