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Gate-controllable photoresponse of nitrogen-doped p-type ZnSe nanoribbons top-gate FETs

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ABSTRACT

Nitrogen-doped *p*-type ZnSe nanoribbons (NRs) were successfully synthesized by a chemical vapor deposition (CVD) method. High-performance field-effect transistors (FETs) based on individual ZnSe NRs with high-κ Si_3N_4 dielectric and top-gate geometry were constructed. In contrast to the nano-FETs with back-gate configuration and SiO_2 dielectric, the top-gate FETs exhibit a substantial improvement in device performances, such as threshold voltage was reduced to a small value of 1.9 V, the transconductance, hole mobility and I_{on}/I_{off} ratio were increased to 864 nS, 10.4 $cm^2\ V^{-1}\ s^{-1}$ and 10^6, respectively. Moreover, the top-gate ZnSe NR FET showed good controllability of photoresponse with fast response speed less than 0.1 s and high I_{light}/I_{dark} ratio up to 10^5, revealing that they are promising candidates for nanoelectronic and optoelectronic applications.

1. Introduction

One-dimensional (1D) II–VI group nanostructures such as nanowires (NWs), nanoribbons (NRs), and nanotubes (NTs) have attracted extensive attention in past decades, due to their great importance in basic scientific research and potential applications [1–4]. They are considered as ideal platforms for exploring novel phenomena at nanoscale and investigating the size and dimensionality dependence of functional properties [5,6]. As a direct wide band-gap II–VI semiconductor, ZnSe, with a band-gap of 2.70 eV at room temperature, is regarded as one of the most important materials for optoelectronic applications [7,8]. ZnSe nanostructures have been intensively studied due to their excellent optoelectronic properties and bipolar doping capability. Hence, a host of optoelectronic applications based on ZnSe nanostructures have been demonstrated, such as light-emitting diodes (LEDs), laser diodes, photodetectors and so on [9–12]. However, undoped and low-level doping ZnSe nanostructures have low conductivity and not suitable for devices applications [12,13]. And high-level doping ZnSe nanostructures based photodetectors usually exhibit poor device performances, such as slow response speed and low current on-off ratio (I_{on}/I_{off}) [14]. Therefore, high-performances photodetectors of ZnSe nanostructures with efficient doping are much demanded to promote the optoelectronic applications of ZnSe nanostructures.

Herein, we report on the synthesis of *p*-type nitrogen-doped ZnSe NRs *via* chemical vapor deposition (CVD) method. High-performance field-effect transistors (FETs) based on individual ZnSe NRs with high-κ Si_3N_4 dielectric and top-gate geometry were constructed, which can function as gate-control photodetectors, and show much enhanced photoresponse properties.

2. Experimental

2.1. Synthesis and characterization of N-doped ZnSe NRs

The N-doped *p*-type ZnSe NRs used in this work were synthesized in an alumina tube furnace *via* CVD. ZnSe powder (Aldrich, 99.99%) placing at the center of the tube furnace was used as the source, and Si substrates coated with a layer of 10 nm Au film were placed in the downstream. NH_3 gas was used as the dopant, filled into tube furnace with Ar gas at a constant flow rate of 85/15 sccm (Ar/NH_3). Afterwards, the ZnSe source was heated up to 1020 °C and maintained at that temperature for 2 h [9,10]. The as-synthesized ZnSe NRs were characterized by X-ray diffraction with Cu Kα radiation (XRD, PA National X' Pert Pro), field-emission scanning electron microscopy (FESEM, JEOL, JSM-6700F), high-resolution transmission electron microscopy (HRTEM, JEOL, JEM-2100) and X-ray photoelectron spectroscopy (XPS, Thermo-VG Scientific, ESCALAB 250).

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2.2. Device construction

To assess the electrical transport and optoelectronic properties of ZnSe:N NRs, FETs were constructed as follows: First, ZnSe NRs were dispersed on SiO_2 (300 nm)/Si ($< 0.1\ \Omega$ cm) substrates. Then, photolithography and e-beam evaporation processes were used to fabricate the source and drain Cu (4 nm)/Au (50 nm) electrodes on ZnSe NRs [10,11]. The Si substrates and SiO_2 served as the bottom-gate and dielectric, respectively. In order to construct top-gate FETs, Si_3N_4 (100 nm), a high-κ gate dielectric layer was deposited on the ZnSe NRs by magnetron sputtering, and then Au (20 nm) top-gate electrodes were fabricated by additional photolithography and lift-off processes. A schematic illustration and an SEM image of the devices are shown in Fig. 2a and inset of Fig. 2c. The electrical transport measurements were conducted with a semiconductor characterization system (Keithley 4200-SCS) with a probe station.

3. Results and discussion

3.1. Characterization of the N-doped ZnSe NRs

Fig. 1a shows a SEM image of ZnSe:N NRs, which reveals that the NRs are clear and smooth with a uniform geometry and widths in the range of 1–3 μm, thicknesses of 50–200 nm and lengths of several tens of micrometers. HRTEM image and the corresponding fast Fourier transform (FFT) pattern are shown in Fig. 1b, indicating that the NR is zinc blende structure with [1-11] growth orientation. In the XRD patterns of the ZnSe NRs (Fig. 1c), all the diffraction peaks can be assigned to zinc blende ZnSe (JCPDS-ICDD 88-2345) and no obvious impurity phases and peak shift are observed, suggesting a single phase of the product. In addition, a peak at 398 eV corresponding to the N 1s was found in XPS detection performed on the ZnSe:N NRs, revealing the successful incorporation of N in the ZnSe NRs.

3.2. Electrical characterization of ZnSe:N NR FETs

Fig. 2b and inset shows the typical electrical transfer characteristics of bottom-gate ZnSe NR FET. The linear curve indicates the good Ohmic contact between the Cu/Au electrodes and the ZnSe NRs. From the gate-dependent source-drain current (I_{DS}) *versus* source-drain voltage (V_{DS}) curves (Fig. 2b), the conductance of the ZnSe:N NR decreases (increases) consistently with the increases (decreases) of the gate voltage in step of 15 V, revealing a pronounced *p*-type conductivity of the ZnSe:N NR. The hole mobility (μ_h) can be estimated to be 2.1 $cm^2\ V^{-1}\ s^{-1}$ based on the

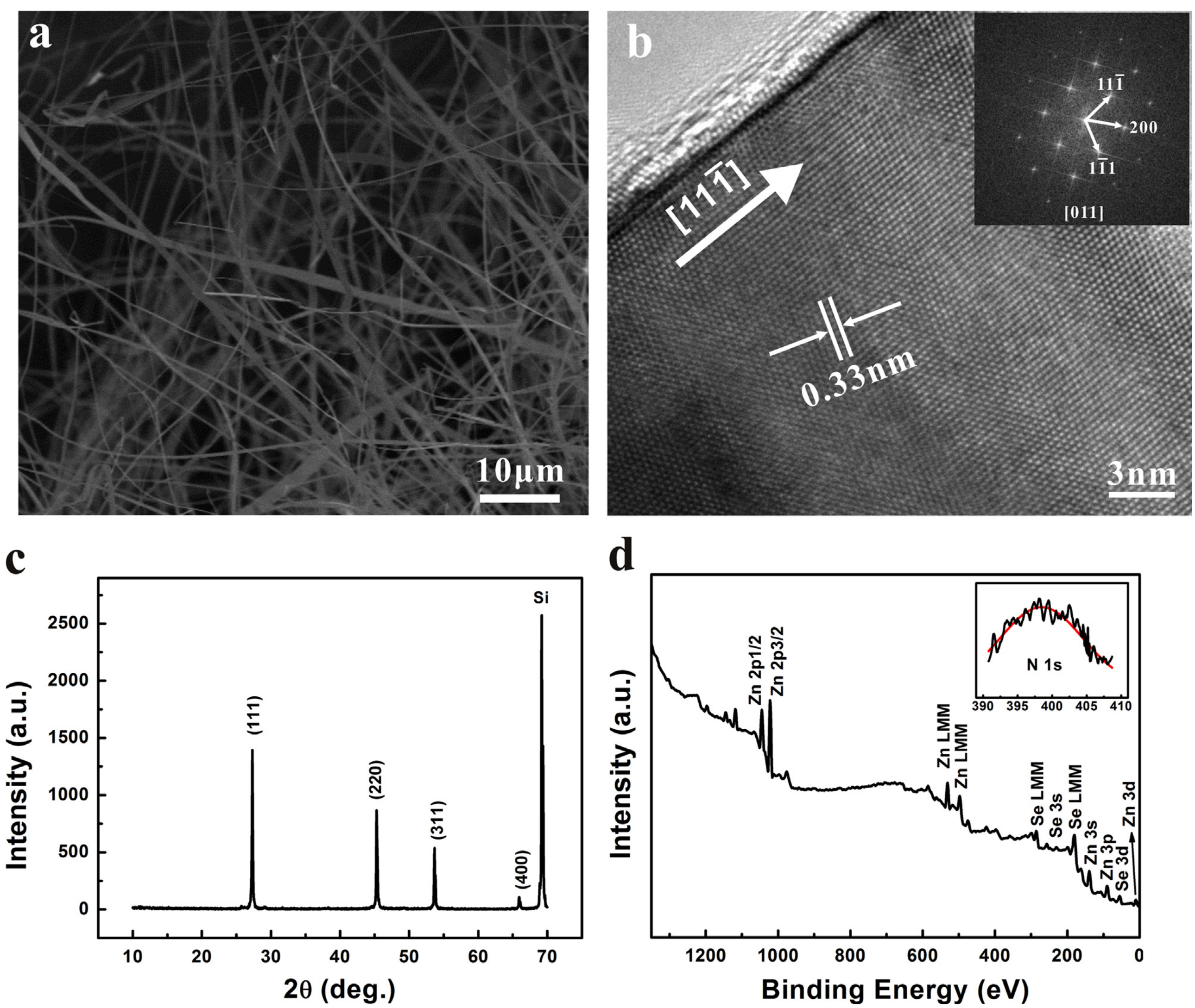

Fig. 1. (a) SEM image, (b) HRTEM image, (c) XRD patterns and (d) XPS spectrum of the N-doped ZnSe NRs. Insets in (b) and (d) show the corresponding FFT pattern and the enlarged N 1s peaks, respectively.