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2-Dimentional photoconductive MoS_2 nanosheets using in surface acoustic wave resonators for ultraviolet light sensing

Peng Zhou [a,b], Changsong Chen [a,b], Xiang Wang [a,b], Baofa Hu [a,b], Haisheng San [a,b,c,*]

[a] Pen-Tung Sah Institute of Micro-Nano Science and Technology, Xiamen University, Xiamen 361005, China
[b] Shenzhen Research Institute of Xiamen University, Shenzhen 518000, China
[c] College of Electronic Science and Technology, Xiamen University, Xiamen 361005, China

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ABSTRACT

2-Dimensional (2D) wide band-gap semiconductor molybdenum disulfide (MoS2) nanosheets as an ultraviolet (UV) photo-conductive material were used in surface acoustic wave (SAW) resonators for UV light sensing. A SAW resonator based on zinc oxide (ZnO) piezoelectric film deposited on glass through radio frequency (RF) magnetron sputtering technique was prepared, in which the sub-microscale gold/chromium (Au/Cr) interdigital transducers (IDTs) and grating reflectors were fabricated onto the ZnO surfaces using the electron beam lithography and lift-off techniques to form the IDTs/ZnO/glass-based SAW resonator with a working frequency at ~1.02 GHz. The MoS_2 nanosheets prepared by electrochemical lithiation process were coated on IDTs region to form a highly sensitive SAW UV sensor, exhibiting an interesting photoresponse behavior to UV radiation. A maximum frequency shift of ~3.5 MHz was found under 365 nm UV radiation with power intensity of 1.466 mW/cm^2, which is attributed to the high resonant frequency (in GHz) and high specific surface area of photo-conductive MoS_2 nanosheets. It is suggested that the adsorption and desorption of oxygen on MoS_2 nanosheets play the dominant roles in the frequency-upshift due to mass loading effect and acoustoelectric effect, meanwhile, acoustoelectric effect also creates the SAW attenuation.

1. Introduction

A surface acoustic wave (SAW) is a kind of acoustic wave that propagates along the surface of a material in a depth less than one or two wavelengths. Lord Rayleigh first described and explained the surface mode of the propagation of an acoustic wave in the elastic solid [1]. Thereafter, it was found that a surface acoustic wave can be easily generated by using interdigital transducers (IDTs) in high quality piezoelectric materials [2]. Since then, SAW devices have been studied and applied in many fields [3]. In recent years more and more researches are focusing SAW devices on sensor applications. It was found that any external perturbation that is taking place on the surface of S=AW devices will affect the propagation of SAW and thus the properties of SAW devices, making the response of SAW devices a sensitive change. This behavior can be utilized for temperature sensors, pressure sensors, humidity sensors, mass sensors, etc. [4–7]. Furthermore, if the surface of a SAW device is covered by a sensing layer, SAW devices can achieve various sensing applications like gas sensors, chemical sensors, biological sensors, optical sensors, etc. [8–11]. Meanwhile, the highly sensitive frequency output allows the fabrication of wireless sensors for remote sensing applications.

The wide band-gap semiconductor like GaN and ZnO with high absorption coefficient for ultraviolet (UV) light have been utilized to develop high sensitivity UV light sensors based on SAW devices [11,12]. Presently, the researches on SAW UV sensors mainly focus on how to improve the UV detection sensitivity. One effective method is to increase the operating frequency of the SAW devices [13]. High working frequency can also be obtained using high acoustic velocity substrate materials (such as diamond) or using an advanced lithography process (such as e-beam or deep-UV lithography) to produce IDTs with sub-micron width in both arm and pitch. Another method is to use UV-sensitive nanostructural materials. For examples, Peng et al. [14] fabricated a $LiNbO_3$-based SAW sensors with ZnO nanowires as the sensitive layer. The device exhibited a higher frequency shift of 65 kHz under UV light intensity of 150 μW/cm^2 than those using the sputtered ZnO film. Two-dimensional (2D) nanomaterials have been receiving great attention in recent years due to their unusual phys-

* Corresponding author at: Pen-Tung Sah Institute of Micro-Nano Science and Technology, Xiamen University, Xiamen 361005, China.
E-mail address: sanhs@xmu.edu.cn (H. San).

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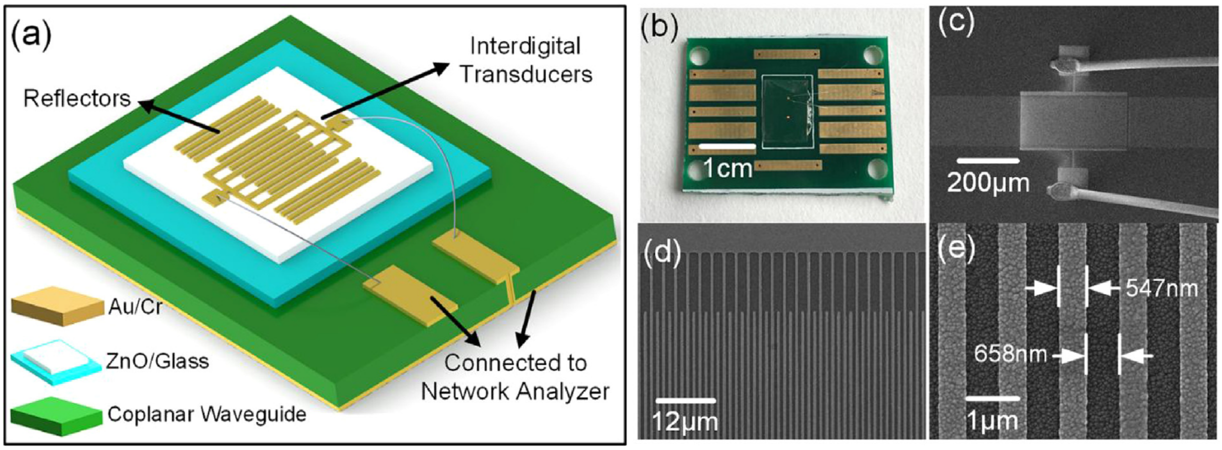

Fig. 1. (a) Schematic 3D structure ZnO/glass-based single port SAW resonator packaged on coplanar waveguide substrate; (b) Packaged SAW resonator; (c) SEM image of SAW resonator; (d) 12 μm and (e) 1 μm spatial resolution of SEM images of IDTs structure.

ical properties as a result of quantum size effect associated with their ultra-thin structure [15]. It is considered that 2-dimentional (2D) photo-conductive nanostructure materials are able to achieve a higher photo-sensitivity than 1D one. Molybdenum disulfide (MoS_2) has wide direct band-gap of 1.8 eV and excellent photo-conductive property in ultraviolet region [16]. Because of the direct bandgap and high mobility, the MoS_2 photodetectors have shown an ultrasensitive photoresponsivity that is ~10^6 better than the first graphene photodetectors (~0.5 mAW^{-1}) [17]. Some other researches also showed the ultrasensitive and ultrafast properties of photodetectors using MoS_2 nanosheets [16,18]. Up to now, the sensing mechanisms of photodetectors using MoS_2 nanosheets still were based on the photoelectric effect. There are a few reports available about the single-layer MoS_2 used in SAW device for the investigation of material properties [19,20].

In the present work, we demonstrate a resonance SAW UV sensor based on ZnO/glass structure with 2D MoS_2 nanosheets coated on IDTs region. The ZnO-based SAW resonator can be operated in frequency of GHz due to the fine IDTs structure with sub-micron width in both arm and pitch, making the resonance SAW UV sensor achieve a high response by an added advantage of high photo-conductive MoS_2 nanosheets.

2. Experimental

2.1. Design and fabrication of SAW resonator

In our design an insulating ZnO film is used as piezoelectric material to fabricate the SAW device. ZnO possesses excellent piezoelectric property, significant electromechanical coupling coefficient, and low fabrication cost, which has been successfully exploited to make commercial SAW devices in thin film form. The Pyrex 7740 glass is used as the substrate. The thickness of ZnO film is a key design parameter for the fabrication of high performance of SAW device. The ratio between the thickness of piezoelectric film and the working wavelength will influence the electromechanical coupling coefficient and sound velocity in material [21]. The resonant frequency of the SAW device is based on the periodicity of IDTs and the velocity of the SAW in piezoelectric material as shown in Eq. (1):

$$f = \frac{v}{\lambda} = \frac{v}{p_i} \quad (1)$$

where f is the resonant frequency, v is the velocity of sound in piezoelectric material, p_i is the periodicity of IDTs, λ is the wavelength of the SAW. To achieve a GHz SAW device, two parameters, v and p_i should be well considered.

Fig. 1(a) shows the schematic 3D structure of ZnO/glass-based single port SAW resonator packaged on coplanar waveguide substrate. For increasing the *Q*-factor of SAW resonator a pair of grating reflectors are located on both sides of the IDTs. Al wire-bonding was used to connect the acoustic transducers with the coplanar waveguide lines which were designed by TXLINE software. For achieving a work frequency of about 1.0 GHz, by means of the finite element method (FEM) using COMSOL Multiphysics software, the thickness of ZnO film deposited on glass substrate was determined to be 2 μm for matching an acoustic wave speed of around 2500 m/s, and the arm-width and pitch-width of IDTs were determined to be 600 nm, making the period of IDTs thus to be 2.4 μm.

ZnO (002) film was grown on glass substrate using radio frequency (RF) magnetron sputtering system. The sputter target was made from high purity Zn (99.99%), the RF magnetron reactive sputtering without intentional substrate heating was performed in a mixed atmosphere of Ar and O_2 flowing at a ratio of 1:1. Very fine Au (60 nm)/Cr (5 nm) IDTs and grating reflectors were fabricated on the surface of ZnO using the electron-beam lithography (EBL) in combination with the Au/Cr lift-off process. The SAW resonator was packaged on the printed circuit board (PCB) with RF coplanar waveguide connected with the electrodes of SAW resonator through Al wire-bonding as shown in Fig. 1(b). Fig. 1(c) shows the SEM image of the complete SAW resonator, and Fig. 1(d) and (e) exhibit different resolution of SEM images of IDTs structure, respectively.

2.2. Coating of MoS_2 nanosheets on ZnO/glass

MoS_2 in its bulk form is generally layered structure with strong covalent bonding in each layer and weak van der Waals forces between layers [22]. It has been reported that the single-layer 2D MoS_2 nanomaterial can be prepared by electrochemical lithiation process [15]. In this process an electrochemical lithiation process is used to make the lithium insertion into the layered structures of MoS_2. By liquid phase ultrasonic exfoliation, single- or few-layer MoS_2 nanosheets can be prepared in large amounts for subsequent thin-film and device fabrications.

For a single port SAW resonator, the nanostructure materials attached on the IDTs will directly change the electrical and mechanical properties of piezoelectric substrate. In this experiment MoS_2 nanosheets as a UV-sensitive and photo-conductive layer were well prepared on the surface of IDTs by spin-coating technique. The spin-coating solution was prepared by dissolving 5 mg of MoS_2