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Development of high frequency $ZnO/SiO_2/Si$ Love mode surface acoustic wave devices

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Abstract

The development of a $ZnO/SiO_2/Si$ based high frequency Love mode surface acoustic wave (LM-SAW) device operating at 1.5 GHz is reported. The growth of ZnO films on SiO_2/(100)Si substrates using pulsed laser deposition has been developed and optimized to obtain efficient Love mode acoustic wave propagation in ZnO. Strain in the ZnO film is measured to be as high as 2.3% and was found to be a function of the SiO_2 thickness. The effects of strain on the frequency response of the LM-SAW devices was studied and characterized for the first time. The highly strained film generated two surface acoustic wave velocities, where the higher velocity is believed to propagate in the less strained top layer of the film, and the lower velocity in the highly strained region of the film interface with the SiO_2. Corresponding to these phase velocities, multiple non-harmonic frequencies of operation for the Love wave device are observed. Annealing the film at 500 °C in air for 45 min reduced the strain to 2%. Reducing the thickness of the SiO_2 layer to 500 Å resulted in reducing the strain substantially to 0.56%, and the devices yielded a phase velocity of 4814.4 m/s in the ZnO guiding layer.

Keywords: ZnO; Love waves; SAW device; Si; SiO_2

1. Introduction

ZnO is a wide band gap semiconductor with important piezoelectric, pressure sensing [1,2] and optoelectronic (UV) properties, suitable for applications in transducers, sensors and UV light emitting/detecting technology [3]. ZnO has been grown epitaxially on sapphire using laser-MBE [3] and pulsed laser deposition (PLD) [4,5]. These techniques have demonstrated high quality epitaxial growth suitable for demonstrating room temperature optically pumped lasing [6] and resonant tunneling in ZnO based heterostructures [5]. One particularly interesting device using ZnO thin films is a surface acoustic wave (SAW) device, which takes advantage of the high piezoelectric properties of ZnO. Typical quartz based SAW devices operate at 30–300 MHz [6] range, while ZnO has the potential to operate at GHz frequencies. One report indicates increased acoustic velocities and GHz operation of ZnO SAW devices when grown on diamond substrates [7], showing that substrate choice is of significant importance to wave propagation. The development of a ZnO based SAW device on Si offers the advantage of integration with CMOS technology and the development of monolithic sensor arrays.

Surface acoustic wave (SAW) sensors have also been used in the detection of bio-materials [8–10]. The principle of operation of the biosensors is that mass loading of the active surface of the SAW device, results in an acoustic velocity change, which is detected as a frequency shift. For sensing in liquid environments, longitudinal bulk modes, Raleigh surface waves, and most Lamb-wave devices present a significant loss of radiation into the liquid

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under test [11,12]. When the mass being sensed is deposited from the liquid phase, the choice of acoustic wave devices is one with a shear horizontal polarization of the displacement, such as shear horizontal (SH) plate mode waves [13], surface transverse waves [14] and Love mode waves [15,16]. Love mode acoustic waves are shear horizontal waves that concentrate the acoustic energy in a guiding layer grown on an appropriate substrate, thus offering the opportunity of higher mass sensitivities [17]. This mode of SAW propagation is dominant depending on the orientation of the guiding layer film. For Love mode propagation in ZnO, the grown film should be along the *c*-axis and the IDTs must be patterned perpendicular to the *c*-axis of the film [18]. Love mode devices for biochemical sensing using SiO_2 as the guiding layer on quartz have been reported previously [15,19,20]. While the growth of ZnO on SiO_2 layers has been reported [21], the effect of SiO_2 layer thickness on the quality of ZnO films has not been studied.

In this work, we have grown high quality ZnO thin films on SiO_2/Si by pulsed laser deposition (PLD), and characterized the structure of the films by X-ray diffraction (XRD). We then fabricated high frequency Love mode SAW devices with optimum performance, and studied the effects of strain on Love wave propagation.

2. Experimental details

Epitaxial (0002) ZnO thin films were grown on SiO_2/(100)Si substrates by pulsed laser deposition (PLD). The PLD growth temperature and oxygen partial pressure were maintained at 250 °C and 10^{-4} Torr respectively, as these conditions have been reported to produce high quality, epitaxial ZnO layers [22–24]. The laser ablation system consisted of a KrF laser at 248 nm, with an energy density of 0.7 J/cm^2, operating at a frequency of 5 Hz. The grown films had a thickness of 1 μm, and they were structurally characterized with X-ray diffraction (XRD) to determine epitaxial quality.

The LM-SAW devices had inter-digitated transducer (IDT) design with micron and submicron feature sizes, fabricated by standard optical photolithography and lift-off techniques. The input and output IDT fingers consist of a 500 Å aluminum layer deposited by e-beam evaporation. The IDTs are aligned perpendicular to the *c*-axis to achieve Love mode propagation [18]. Two sets of devices were developed. Device A was designed to achieve minimum insertion losses and is suitable for operation in the sub-GHz range ($\lambda = 6.8$ μm), with device finger width and spacing of 1 μm and 2.4 μm respectively. Device B was designed to achieve a fundamental frequency of operation in the GHz range ($\lambda = 3.2$ μm) with both finger width and spacing of 0.8 μm. The number of finger pairs in each device, N_p is 15. The high frequency *s*-parameters of the LM-SAW devices were evaluated using a HP8510C parametric network analyzer in the frequency range of 300 kHz and 3 GHz. In order to achieve impedance matching to the load line of 50 Ω impedance, the length of the transmission lines leading to the measuring pads of the LM-SAW device and the thickness of the deposited Al needed to be optimized.

3. Experimental results and discussion

3.1. Structural properties

X-ray diffraction was used to evaluate the crystalline quality of the grown ZnO films on the SiO_2/Si substrate system. Fig. 1a shows the θ–2θ scan of a 1 μm thick ZnO film grown on a 2000 Å SiO_2 layer on (001)Si. The peak at 35.2° indicates a predominant orientation along

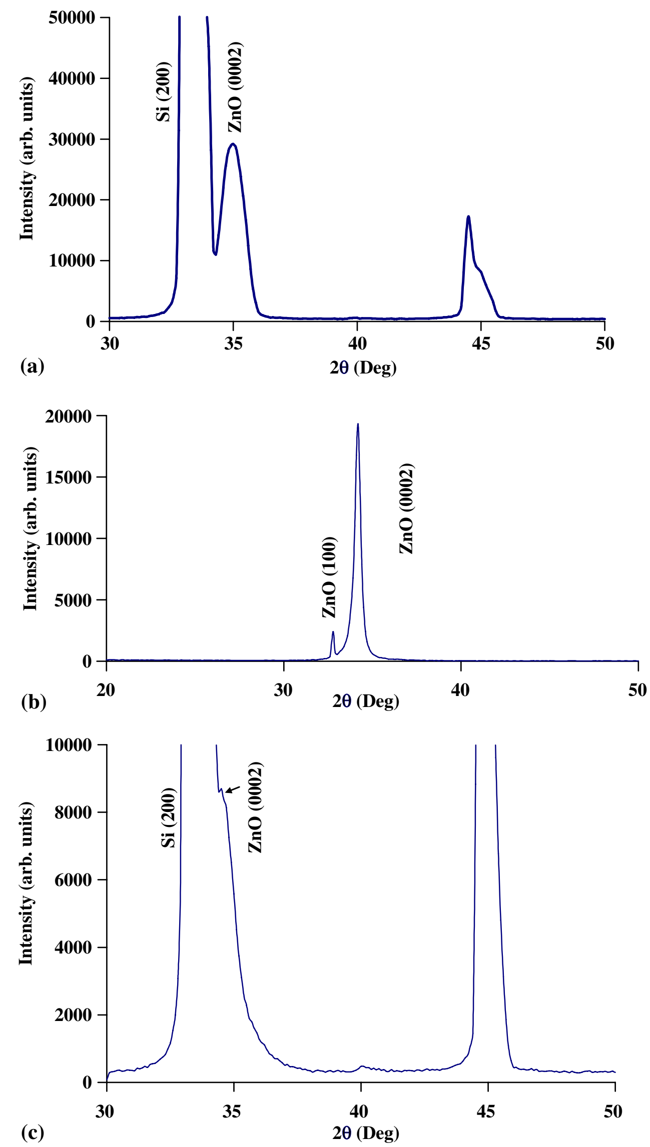

Fig. 1. X-ray diffraction θ–2θ scan of (a) ZnO/SiO_2/(100)Si with SiO_2 thickness of 2000 Å. The (0002) ZnO peak is at 35.2°, indicating a highly strained film with a strain of 2.3%, (b) ZnO/(100)Si. The (0002) ZnO peak is at 34.3°, indicating a strain of only 0.31%, and (c) ZnO/SiO_2/(100)Si with SiO_2 thickness of 500 Å. The (0002) peak is at 34.5° indicating a strain of only 0.56%.