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Comparative analysis of oxide phase formation and its effects on electrical properties of SiO_2/InSb metal-oxide-semiconductor structures

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ABSTRACT

We report on the changes in the interfacial phases between SiO_2 and InSb caused by various deposition temperatures and heat treatments. X-ray photoelectron spectroscopy (XPS) and Raman spectroscopy were used to evaluate the relative amount of each phase present at the interface. The effect of interfacial phases on the electrical properties of SiO_2/InSb metal-oxide-semiconductor (MOS) structures was investigated by capacitance–voltage (C–V) measurements. The amount of both In and Sb oxides increased with the deposition temperature. The amount of interfacial In oxide was larger for all samples, regardless of the deposition and annealing temperatures and times. In particular, the annealed samples contained less than half the amount of Sb oxide compared with the as-deposited samples, indicating a strong interfacial reaction between Sb oxide and the InSb substrate during annealing. The interface trap density sharply increased for deposition temperatures above 240 °C. The C–V measurements and Raman spectroscopy indicated that elemental Sb accumulation due to the interfacial reaction of Sb oxide with InSb substrate was responsible for the increased interfacial trap densities in these SiO_2/InSb MOS structures.

1. Introduction

The interfacial phases between SiO_2 and InSb have attracted great interest over the last decade, with the aim of improving the performance of InSb-based devices [1,2]. Since the report on the SiO_2/InSb interface by Langan et al. [3], it has been the subject of intensive study. Various techniques such as plasma enhanced chemical vapor deposition (PECVD), photo-assisted CVD, remote PECVD, and anodization have been used to deposit high-quality dielectrics onto InSb substrates [4–8]. Also, many surface treatments such as cleaning with organic solvents [9], vapor etching [10], and sulfur passivation [11] have improved the interfacial properties of SiO_2/InSb.

The importance of interfacial reactions and of the resultant phases between SiO_2 and InSb is well known [7,12–15]. Interactions at the SiO_2/native oxide interface, as well as at the thin native oxide/InSb interface, play a dominant role in defining the composition of the interfacial phases and electrical properties of InSb metal-oxide-semiconductor (MOS) structures [7]. Vasquez et al. reported on the interfacial chemistry of CVD SiO_2 films deposited onto a thin native oxide on an InSb substrate [15]. They observed a significant interaction between the native oxide and the InSb and the formation of a few layers of excess elemental Sb at the SiO_2/InSb interface. In-depth studies on the interfacial reactions between the native oxide and InSb were also conducted by Bregman et al. They analyzed this interface by Auger electron spectroscopy and obtained quantitative compositional information on the interfacial oxide [16,17]. Many reports by Okamura et al. [10], Takahashi et al. [18], and Avigal et al. [19] confirmed the importance of the interfacial phases in determining the electrical properties of the SiO_2/InSb interface.

However, despite the large number of studies on SiO_2/InSb interfacial phases, the dependence of the composition of interfacial oxides on the SiO_2 deposition temperature is not completely understood [15,19]. Moreover, the interfacial phases between as-deposited PECVD SiO_2/InSb structures and annealed ones have not been compared quantitatively.

We analyzed the formation of interfacial phases at the SiO_2/InSb interface, the oxidation of In and Sb, and the formation of elemental Sb at the interface at various deposition and annealing temperatures by X-ray photoelectron spectroscopy (XPS) and Raman spectroscopy. Capacitance–voltage (C–V) measurements yielded interface trap densities in the samples at various deposition temperatures. Finally, we

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investigated the effects of the interfacial phases on the electrical properties of SiO_2/InSb MOS structures and the correlations between changes in interfacial phases and interface trap densities.

2. Experimental details

Samples were prepared using undoped InSb substrates with an electron concentration of 2–8.5×10^{14} cm^{-3}. Native oxides were removed by a dilute HF solution (HF:deionized water = 1:10). Samples were rinsed with deionized water for 2 min and blow-dried with N_2. Then, a 100 nm-thick SiO_2 layer was deposited by PECVD at 120, 160, 200, 240, or 300 °C. The source gases were SiH_4 (160 sccm) and N_2O (1500 sccm), and the carrier gas was N_2 (240 sccm). The chamber pressure was maintained at 550 mTorr (73.33 Pa) during the deposition. The RF power and frequency were 60 W and 187 kHz, respectively. Samples deposited at 120 °C were put into a furnace and annealed at 300 °C for 10 or 30 min in an N_2 ambience. We investigated the changes in interfacial phases between SiO_2 and InSb by measuring an XPS depth profile and Raman spectra. The systems used were a Sigma Probe (ThermoVG, UK) and a LabRam HR (Jobin-Yvon, FRA) with an Ar-ion laser (514 nm), respectively. We probed the buried interfaces by sputter-etching the samples with 2 μA, 2 kV Ar ions, rastering over a sample area of 2×2 mm^2, and by repeating the XPS measurements as the samples were sputter-etched by 3 to 5 nm near the SiO_2/InSb interface until the oxide signals disappeared completely. We chose the spectra containing the largest amount of oxide phases as representative of the center of the interface. The binding energy scale of the XPS spectra has been referenced to the In $3d_{5/2}$ peak at 444.5 eV.

InSb MOS structures were fabricated to calculate interface trap densities at the SiO_2/InSb interface by C–V measurements. Gold deposition by an evaporator formed an upper contact, and titanium was used as an adhesion layer for gold top electrode. The samples were then cooled down to 77 K inside a cryostat, and an Agilent 4980A LCR meter measured the C–V characteristics at 1 MHz. Hence, we calculated the interface trap densities by the Terman method [20]. The sweep voltage ranged from −4 V to +4 V and the sweep rate was maintained at 0.1 V/s for all samples.

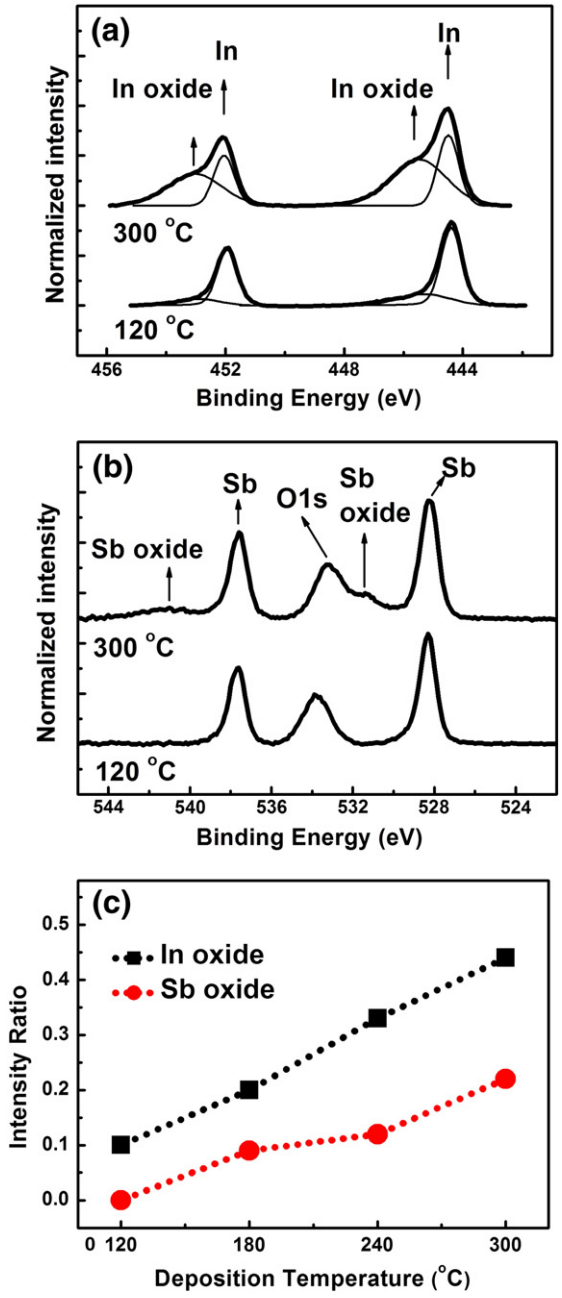

Fig. 1. XPS spectra of the SiO_2/InSb interface with (a) the In 3d peak and (b) the Sb 3d peak for SiO_2 deposited onto InSb at 120 and 300 °C. The In oxide (In $d_{5/2}$ 445.5 eV) and Sb oxide (Sb $d_{5/2}$ 531.3 eV) peaks were observed in samples deposited at 300 °C. (c) Intensity ratios for In oxide and Sb oxide deposited at various temperatures.

3. Results and discussion

Fig. 1(a) shows the XPS spectra for In 3d at the SiO_2/InSb interface in the samples deposited at 120 and 300 °C. The peak position for In $3d_{5/2}$ on the InSb substrate was 444.5 eV, and that for the In oxide was 445.5 eV [21]. We observed a significant increase in the peak intensity at 445.5 eV in the sample deposited at 300 °C, indicating the formation of a large amount of indium oxide. Antimony oxide phases were also analyzed by the same method. Fig. 1(b) shows the XPS spectra for Sb at the SiO_2/InSb interface in the samples deposited at 120 and 300 °C. The Sb $3d_{5/2}$ peak for the InSb substrate appears at 528.3 eV, with the shoulder peak corresponding to Sb oxide at 531.3 eV [21]. As above, the Sb oxide peak intensity increased with the deposition temperature. The shoulder peak was observed at 531.3 eV in the sample deposited at 300 °C, suggesting that a substantial amount of Sb oxides was formed at the interface. We quantitatively analyzed this amount by deconvoluting the XPS spectra. We defined *the intensity ratios for each oxide* as the ratios of the integrated intensity of each oxide peak to that of their respective elements from the InSb substrate. The integrated XPS peaks for In and Sb from the substrate were measured after the complete removal of oxides by

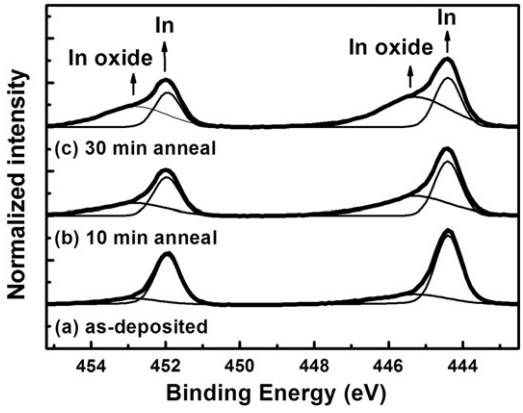

Fig. 2. XPS spectra around the In 3d peak at the SiO_2/InSb interface. All samples were deposited at 120 °C, and measured (a) as-deposited, (b) after annealing at 300 °C for 10 min, and (b) after annealing at 300 °C for 30 min. The In $d_{5/2}$ peak of the InSb substrate is located at 444.5 eV, and that of In oxide at 531.3 eV.