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Rare-earth gate oxides for GaAs MOSFET application

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Abstract

Rare-earth oxide films for gate dielectric on *n*-GaAs have been investigated. The oxide films were e-beam evaporated on S-passivated GaAs, considering interfacial chemical bonding state and energy band structure. Rare-earth oxides such as Gd_2O_3, $(Gd_xLa_{1-x})_2O_3$, and Gd-silicate were employed due to high resistivity and no chemical reaction with GaAs. Structural and bonding properties were characterized by X-ray photoemission, absorption, and diffraction. The electrical characteristics of metal-oxide-semiconductor (MOS) diodes were correlated with material properties and energy band structures to guarantee the feasibility for MOS field effect transistor (FET) application.

Gd_2O_3 films were grown epitaxially on S-passivated GaAs (0 0 1) at 400 °C. The passivation induced a lowering of crystallization temperature with an epitaxial relationship of Gd_2O_3 (4 4 0) and GaAs (0 0 1). A better lattice matching relation between Gd_2O_3 and GaAs substrate was accomplished by the substitution of Gd with La, which has larger ionic radius. The in-plane relationship of $(Gd_xLa_{1-x})_2O_3$ (4 4 0) with GaAs (0 0 1) was found and the epitaxial films showed an improved crystalline quality. Amorphous Gd-silicate film was synthesized by the incorporation of SiO_2 into Gd_2O_3. These amorphous Gd-silicate films excluded defect traps or current flow path due to grain boundaries and showed a relatively larger energy band gap dependent on the contents of SiO_2. Energy band parameters such as ΔE_C, ΔE_V, and E_g were effectively controlled by the film composition.

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Keywords: GaAs; MOS; Gd_2O_3; $(Gd_xLa_{1-x})_2O_3$; Gd-silicate; S-passivation; Epitaxial growth; Amorphous; Band gap; Band offset

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1. Introduction

GaAs metal-oxide-semiconductor field-effect transistors (MOSFETs) show considerable interest and continue to be developed for applications such as high-efficiency power amplifiers and high-speed, low-power digital processors [1]. Although an introduction of large applied input voltage and a simple circuit design are possible with MOS gate, most of currently commercialized III–V devices employ a metal-semiconductor field-effect transistor because of deleterious oxide/substrate interactions. Undesired interfacial products and electrically active defects could lower band-offset values of MOS structure. Thus, surface passivation of GaAs is required to minimize a deposition-induced degradation.

Especially with oxide–GaAs system, single crystalline or amorphous oxide films have been recently introduced to gate dielectrics on GaAs since polycrystalline films showed electrical and structural degradation. An epitaxial Gd_2O_3 films have been reported with the development of molecular beam epitaxy and ultra high vacuum process [2,3]. However, there exists a lattice mismatch of +1.9% and −3.9% when considering a rectangular super-lattice matching of 3.528 nm × 1.535 nm. It could induce misfit dislocation at the interface and pinning of Fermi level on the surface of *n*-GaAs. On the other hand, amorphous oxide films of Al_2O_3 and Ga_2O_3 showed high breakdown field and sharp interface in atomic scale with low interface state density with *n*-GaAs [4,5].

In this work, rare-earth oxide films such as Gd_2O_3, $(Gd_xLa_{1-x})_2O_3$, and $(Gd_2O_3)_{1-x}(SiO_2)_x$ were employed as gate dielectric on S-passivated GaAs. Cation Gd is substituted with La of larger ionic radius to reduce lattice mismatch

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between (4 4 0) of the oxide film and (0 0 1) of GaAs. In addition, SiO_2 was incorporated to Gd_2O_3 for the control of dielectric band gap and band offset with regard to *n*-GaAs. Therefore, we have focused our attention on the change of band structure in Gd-related oxide/*n*-GaAs system. The electrical properties could be well understood in reference to the band offset change at the oxide/GaAs structure.

2. Experimental procedure

An *n*-GaAs (0 0 1) wafer, doped with Si of $\sim 8 \times 10^{16}$ cm^{-3}, was used in this experiment. Au/Ge/Ni/Au was e-beam evaporated on the backside of the wafer and alloyed by rapid thermal anneal at 400 °C under N_2 ambient for 30 s to form a low resistive ohmic contact [6]. Prior to the deposition, the wafer was cleaned to remove surface organics and native oxide. The surface of GaAs was passivated with sulfur by immersing in $(NH_4)_2S$ solution [7].

Gd_2O_3 and a series of $(Gd_xLa_{1-x})_2O_3$ films were grown using e-beam evaporation of powder-packed oxide targets under 2×10^{-7} Torr at 400 °C. $(Gd_2O_3)_{1-x}(SiO_2)_x$ were deposited from mixed oxide targets at 300 °C of substrate-anneal. The deposition rate was 0.2 nm/s and it was measured by using a quartz-crystal microbalance. The total oxide thickness ranged from 18 to 20 nm, and it was verified by using ellipsometry and X-ray reflectivity; the composition was checked by using Rutherford backscattering spectrometry and X-ray photoelectron spectroscopy (XPS, ESCALAB220i-XL). Several nanometers thick films were also prepared to characterize the interfacial bonding state by photoemission spectroscopy. The occupied and unoccupied states were mapped at the 4B1 beam line of Pohang Light Source with synchrotron radiation photoemission spectroscopy (PES) and X-ray absorption spectroscopy (XAS), respectively. Structural measurements were carried out using single-crystal XRD on a triple-axes four-circle diffractometer (Bruker D8 GADDS) with a Cu Kα source.

MOS diodes were fabricated with circular Au dots on the oxide surface for top electrode by using e-beam deposition. Capacitance–voltage (*C*–*V*) and current–voltage (*I*–*V*) measurements were accomplished using HP4284A and HP4145B, respectively.

3. Results and discussion

3.1. Gd_2O_3/n-GaAs

Fig. 1 shows θ–2θ scan of 20 nm-thick Gd_2O_3 films formed at various substrate temperatures. The effect of sulfur passivation layer on the crystallization of Gd_2O_3 films was interpreted. The crystalline phase was formed from 350 °C on the surface of HCl-cleaned GaAs (0 0 1). The diffraction of (4 4 0) plane was observed behind the (4 3 1) plane. However, the S-passivated GaAs surface reduced the crystallization temperature below 300 °C. In particular, the film grows with a preferred orientation of [4 4 0]. The in-plane epitaxial relationship is proved to be [0 0 1] Gd_2O_3//[1,−1,0] GaAs and [1 1 0] Gd_2O_3//[0 0 1] GaAs by phi scan analysis [8]. Therefore, we

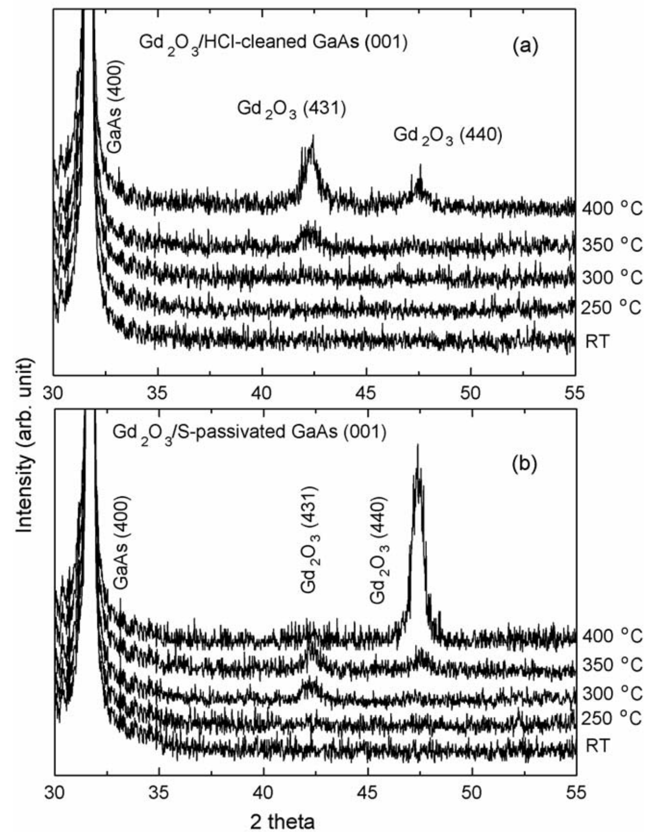

Fig. 1. X-ray diffraction pattern of in situ grown Gd_2O_3 films on (a) HCl-cleaned GaAs and (b) S-passivated GaAs (0 0 1).

can categorize the role of sulfur passivation layer as preventing air oxidation and lowering crystallization temperature. It implies that the formation of interfacial oxides such as As–oxide and Ga–oxide prohibit the phase formation of Gd_2O_3 and repress the effect of substrate orientation. To examine interfacial bonding characteristics, Gd_2O_3 films of about 3 nm thick were deposited on GaAs surface at various temperatures considering the information depth of Ga and As photoelectrons [9]. Fig. 2 describes 3d core level spectra of Ga and As after the deposition of Gd_2O_3 film on HCl-cleaned or S-passivated GaAs surface as a function of deposition temperature. The inelastic background in the 3d regions was subtracted using the Shirley method for the decomposition of spectra [10]. Before the deposition of Gd_2O_3, large amounts of As–As (elemental As) and As–O (As_2O_3) bonds were observed on the HCl-cleaned GaAs surface [11]. While extra As–S bonds were observed after the sulfidation, Ga–O bond was not detected in any case. After the deposition of Gd_2O_3, As–O ($\Delta E = \sim 2.5$ eV), and As–As ($\Delta E = \sim 0.7$ eV) bonding states [12] were found besides As–Ga on the HCl-cleaned surface as given in Fig. 2a. As–O bonds in As_2O_3 began to decompose at 200 °C and the continuous decomposition of As–O bond induced the formation of Ga–O bonds in Ga_2O_3. S-passivated surface showed a new bonding state with 0.7 eV of positive chemical shift from the binding energy of Ga–As bond, corresponding to the formation of Ga–S bond due to the dissociation of As–S bond [13]. The interfacial oxide could be

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