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Current-transport properties of atomic-layer-deposited ultrathin Al_2O_3 on GaAs

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Abstract

We report detailed current-transport studies of ultrathin Al_2O_3 dielectrics on GaAs grown by atomic layer deposition (ALD) as a function of film thickness, ambient temperature and electric field. The leakage current in ultrathin Al_2O_3 on GaAs is comparable to or even lower than that of the state-of-the-art SiO_2 on Si, not counting on high dielectric constant for Al_2O_3. By measuring leakage current at a wide range of temperatures from 133 K to 475 K, we are able to identify the electron transport mechanism and measure the thermal-activation energy of the ultrathin oxide films. This thermal-activation energy is proposed as a parameter to generally characterize the quality of ultrathin dielectrics on semiconductors.

Keywords: Atomic layer deposition; GaAs MOSFET; Thermal-activation energy

1. Introduction

The search for alternative gate dielectrics has attracted great attention in the past years because technology roadmaps predict the need for high-*k* gate dielectric for Si-based complementary metal-oxide-semiconductor field-effect-transistors (MOSFETs) technology nodes beyond 65 nm [1]. In order to further drive complementary metal-oxide-semiconductor (CMOS) integration, functional density, speed and power dissipation, and extend front-end fabrication of CMOS to and beyond the 22-nm node, novel device structures and gate stacks are needed. One emerging research field is to use III–V compound semiconductor materials as conduction channels to replace traditional Si or strained Si [2], meanwhile integrate these high mobility materials with novel high-*k* dielectrics and heterogeneously built on silicon or silicon on insulator (SOI). The ultimate CMOS technology should include the following four features: (1) high-*k* dielectric and metal gate stack (2) high mobility carrier channels (3) ultra short gate lengths below 100 nm, and (4) heterogeneously, probably selectively, built on silicon or SOI.

Atomic layer deposition (ALD) is an ultra-thin-film deposition technique based on sequences of self-limiting surface reactions enabling thickness control on atomic scale. We have applied ALD to grow high-*k* gate dielectrics on III–V compound semiconductors with high-mobility channels and demonstrated GaAs and GaN MOSFETs with excellent device performance [3–6]. The previous work is focused on applying this novel III–V MOSFET structures to booster discrete devices for high-speed and high-power applications, which could tolerate the interface trap density of $10^{11}\,cm^{-2}\,eV^{-1}$ at this novel ALD/III–V semiconductor material system. The new research interests are focused on III–V CMOS technology for large-scale

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integration or digital applications, which requires not only much better and reliable oxide/semiconductor interface properties, but also high-*k* gate dielectric materials with further scalability to sub-0.7-nm effective inversion gate-oxide thickness. For above reasons, the current-transport studies of ultrathin high-*k* oxides on GaAs are of great importance for ultimate CMOS technology, although the electrical properties of ALD Al_2O_3 films on the order of ∼1000 Å have been investigated by several research groups already [7–15]. In this paper, we report detailed current-transport studies of ultrathin Al_2O_3 dielectrics on GaAs grown by ALD. The leakage current in ultrathin Al_2O_3 on GaAs is comparable to or even lower than that of the state-of-the-art SiO_2 on Si [15], not counting the high-*k* dielectric properties for Al_2O_3, which is more than a factor of 2 higher compared to SiO_2. The thinnest Al_2O_3 studied is only 12 Å which has the equivalent oxide thickness of only 4.7 Å, assuming the dielectric constant of the grown film is 10, the typical value of high-quality ALD Al_2O_3. By measuring leakage current at low temperatures from 133 K to 273 K and at elevated temperatures from 273 K to 475 K, it enables us to measure the thermal-activation energy of ultrathin oxide films. This thermal-activation energy is proposed as a material parameter to generally characterize the quality of ultrathin dielectrics on semiconductors. Three different carrier transport regimes – Frenkel–Poole emission, Ohmic and tunneling – are discussed in the frame of experimental data.

Al_2O_3 is a widely used insulating material for gate dielectric, tunneling barrier and protection coating due to its excellent dielectric properties, strong adhesion to dissimilar materials, and its thermal and chemical stability. Al_2O_3 has a high bandgap (∼9 eV), a high breakdown electric field (5–10 MV/cm), a high permittivity (8.6–10) and high thermal stability (up to at least 1000 °C) and remains amorphous under typical processing conditions. Compared to the conventional methods to form thin Al_2O_3 films, i.e., by sputtering, electron beam evaporation, chemical vapor deposition or oxidation of pure Al films, the atomic layer deposited (ALD) Al_2O_3 is of much higher quality in terms of homogeneity, thickness control and stoichiometry. The leakage current in ultrathin Al_2O_3 on GaAs is low. The breakdown electric field of Al_2O_3 is measured as high as 10 MV/cm for films thicker than 50 Å, which is near the bulk breakdown electric field for SiO_2. A significant enhancement on breakdown electric field up to 30 MV/cm is observed as the film thickness approaches to 10 Å [15].

2. Experiments

The starting materials were 2 in. Si-doped GaAs wafers with the doping concentration of $6–8 \times 10^{17}$ cm^{-3}. Before Al_2O_3 deposition, substrates were treated with a diluted HF solution to remove the native oxide and eliminate the interfacial layer sometimes existing at the Al_2O_3/GaAs interface [16]. The wafers were transferred immediately to an ASM Pulsar2000^{TM} ALD module to grow ALD films. An excess of each precursor was supplied alternatively to saturate the surface sites and ensure self-limiting film growth. Al_2O_3 films were grown using alternating pulses of $Al(CH_3)_3$ (the Al precursor) and H_2O (the oxygen precursor) in a carrier N_2 gas flow. Different Al_2O_3 oxide layers of the thickness of 12, 15, 20, 25, 30, 40, 50, 60 Å were deposited at a substrate temperature of 300 °C. The number of ALD cycle was used here to control the thickness of deposited films. All deposited Al_2O_3 films in this paper are amorphous, which is favorable for gate dielectrics. The 600 °C O_2 anneals were performed *ex situ* in a rapid thermal annealing chamber following film deposition. A 1000 Å thick Au film were deposited on the back side of GaAs wafers to reduce the contact resistance between GaAs wafers and the chuck of the measurement setup. The oxide leakage currents were measured through capacitors which were fabricated using 3000 Å Au top electrodes.

3. Results and discussion

Fig. 1 shows the leakage current density (J_L) versus the applied potential on the capacitor (V_g) of 20 Å Al_2O_3 for a set of temperatures measured from 300 K to 475 K. Voltage bias is applied on the metal electrode with respect to the grounded GaAs substrate. The positive biased curve and the negative biased curve are virtually identical. The slight difference is believed to be mainly due to the difference of the barrier heights at the Au–Al_2O_3 and Al_2O_3–GaAs interfaces, and the effects associated with the drift of surface charges at the interfaces. The Al_2O_3 dielectric films are highly electrically insulating. Very low leakage current density of $\sim 10^{-10}$ to 10^{-8} A/cm^2 exhibits around zero bias. This could do with the fact that Al is electropositive +3 and has a strong affinity to oxygen. The 20 Å Al_2O_3 with the equivalent oxide thickness of only 7.8 Å still shows well-behaved direct tunneling characteristic

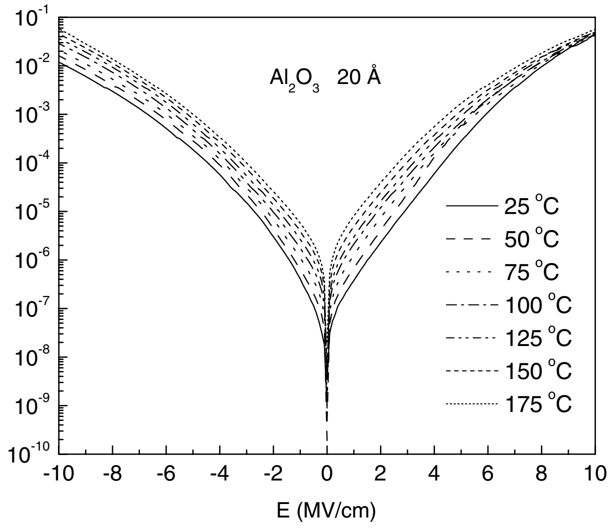

Fig. 1. Measured leakage current density J_L versus gate bias V_g for ALD Al_2O_3 films on GaAs with the film thickness of 20 Å for $298\ K \leqslant T \leqslant 448\ K$.

and doesnot break down at the electric field of 10 MV/cm. Compared to the state-of-the-art SiO_2 on Si using poly-silicon gate, the leakage current density of Al_2O_3 on GaAs is one order of magnitude lower. Because of the enhancement of the electric breakdown strength for ultrathin oxides, 20 Å Al_2O_3 could sustain electric stress at 10 MV/cm or 2 V bias as shown in Fig. 1. The breakdown electric field is beyond 15 MV/cm for 20 Å Al_2O_3 film [15]. The plot shows a slight increase in current density with increasing temperature in general. It is different from a pure tunneling mechanism which has no temperature dependence.

The similar temperature dependence is also observed from the film thickness of 30 Å down to 12 Å. We focus on the representative data obtained from 12 Å thick Al_2O_3 film measured at temperatures ranging from 133 to 475 K. Fig. 2 shows plot of the current density versus $1/T$ for electric field of 4.2 MV/cm. One notes that in the above given field range for temperatures lower than 200 K or for $1000/T$ greater than $5/K$, the current on temperature dependence is significantly slow down compared to that at higher temperatures. Based on the above findings and well-established model for current-transport mechanisms in thick oxides [17], it is proposed that the conduction-current density J_L is the sum of three contributions:

$$J_L = J_{FP} + J_{Ohm} + J_T, \tag{1}$$

where

$$J_{FP} = C_1 E_{ox} \exp\{-q[\Phi_{tr} - (qE_{ox}/\pi\varepsilon_0\varepsilon_d)^{1/2}]/kT\}, \tag{2}$$

$$J_{Ohm} = C_2 E_{ox} \exp(-q\Phi_2/kT), \tag{3}$$

$$J_T = C_3 E_{ox}^2 \exp(-E_3/E_{ox}). \tag{4}$$

In Eq. (2), E_{ox} is the electric field in oxide, q the electronic charge, Φ_{tr} the barrier heights or the depth of the trap-potential well, ε_0 the permittivity of free space, ε_d the dynamic dielectric constant, k the Boltzmann constant, and T the temperature in K. Current density J_{FP} is known as the Frenkel–Poole effect term due to field-enhanced thermal excitation of trapped electrons into the conduction band. The proportionality constant C_1 is a function of density of the trapping centers. Current density J_{Ohm} is ascribed to the hopping of thermally excited electrons from one isolated state to another, showing an Ohmic I–V characteristic. It is exponentially dependent on temperature with a thermal-activation energy $q\Phi_2$. C_2 is a constant depending on different insulators. Current density J_T is due to field ionization of trapped electrons into the conduction band. It is a tunneling process essentially independent of temperature. C_3 and E_3 in Eq. (4) are functions of effective mass and the depth of the trap-potential well. For ultrathin Al_2O_3 on GaAs as observed in Fig. 2, J_{Ohm} is the dominant part, while J_{FP} could be observed as T tends to be higher than 400 K and J_T could become dominate once T goes to even lower temperatures than 133 K.

At high fields and high temperatures, the Frenkel–Poole current density J_{FP} dominates the current conduction for oxides with the thickness 40 Å and up [15]. The current transport for ultrathin oxide films is quite different from the standard model discussed above. Fig. 3 is the plot of J_L (in natural log) versus $1/T$ from the 20 Å oxide sample at four different electric field strengths. Linear fits are added along the data points. These are representative data for different film thickness and at different electrical field strength. At the electric field between 5–10 MV/cm, the fitting slopes are almost same with the error less than 5%. This J_L versus $1/T$ relationship can not be depicted by traditional Frenkel–Poole model which strongly depends on the electric fields across the insulating films as described as J_{FP} at Eq. (1). The measured current density J_L can be

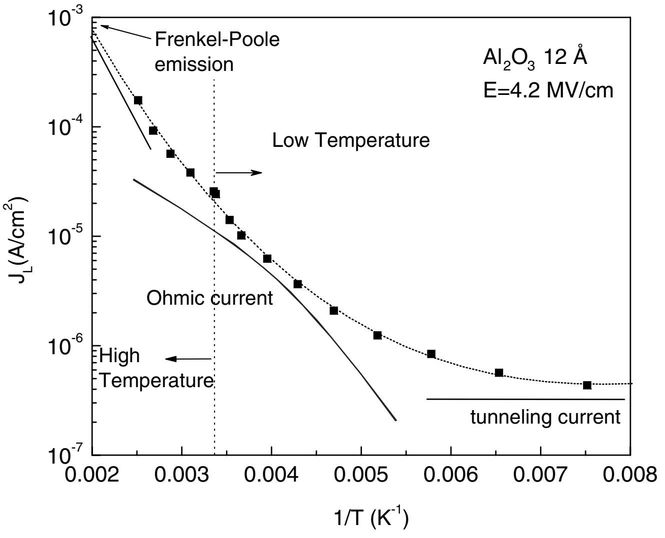

Fig. 2. J_L versus $1/T$ plot for the measured data for a 12 Å thick ALD Al_2O_3 film on GaAs at the fixed electric field of 4.2 MV/cm. The solid lines are eye-guided to show three different current-transport regimes for thin oxide film. The vertical dash line marks room temperature at x-axis.

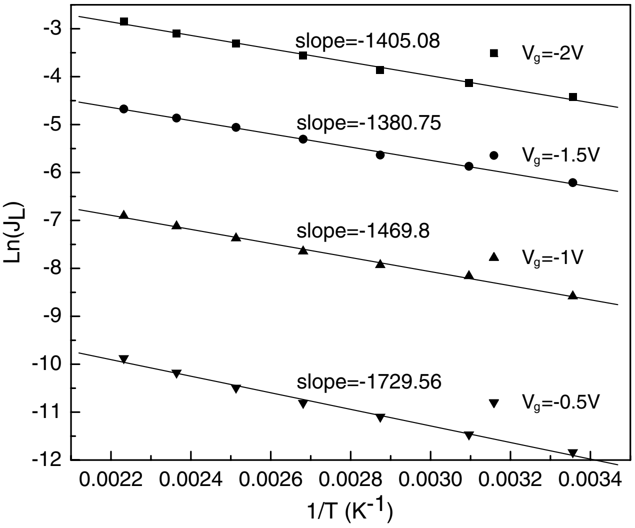

Fig. 3. J_L in natural log versus $1/T$ plot for the measured data for a 20 Å thick ALD Al_2O_3 film on GaAs at the different gate biases from −0.5 V to −2 V. The solid lines are fitted to the measured data. The slopes of fitted lines for $V_g = -2$ V to −1 V are almost same, while the slope for $V_g = -0.5$ V is slightly different.

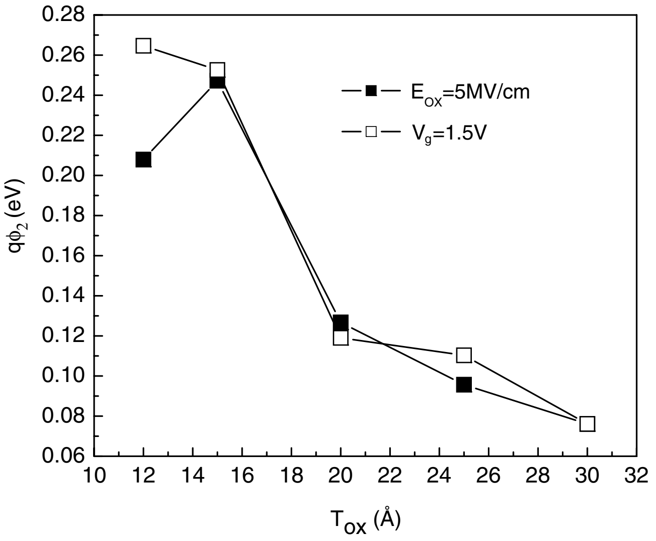

Fig. 4. The summary plot of thermal-activated energy $q\Phi_2$ versus the oxide thicknesses of the ALD Al_2O_3 films on GaAs at a constant electric field of 5 MV/cm and a constant gate bias of $V_g = -1.5$ V.

ascribed that the thermally excited electrons hop from one isolated state to another, showing an Ohmic *I–V* characteristic. These fitted slopes suggest the current density depends solely and exponentially on temperature and the thermal-activation energy $q\Phi_2$, as described by Eq. (2). The thermal-activation energy $q\Phi_2$ could be used as an important parameter to characterize the quality of ultrathin oxide. If the oxide is of extremely high-quality in bulk and interface, such as thermal SiO_2 on Si with interface trap density of $10^9\ cm^{-2}\ eV^{-1}$, the current-transport in ultrathin SiO_2 is pure direct tunneling and independent on temperatures. Φ_2 for such kind of ideal films is near zero. Any material systems, i.e., high-*k* dielectrics on Si or III–V compound semiconductors, could have finite value of Φ_2 due to the imperfection of bulk or interface properties.

By processing the leakage current measurements from all the ALD Al_2O_3 on GaAs samples with various oxide thicknesses from 30 Å down to 12 Å, we plotted the thermal-activation energies $q\Phi_2$ with their corresponding oxide thicknesses, as shown in Fig. 4. Here the plot suggests a trend of decrease in thermal-activation energy as the oxide thickness increases. As the film thickness is more than 30 Å or the film property approaches bulk, $q\Phi_2$ approaches zero or the temperature dependent current-transport diminishes. It demonstrates the interface traps have less effect on bulk properties of oxides once the film thickness is beyond 40 Å and the ALD process does produce high-quality Al_2O_3. When the film approaches to ultrathin limit, the quality of interface, in particular for GaAs case, plays more important role and has negative effect on the ultrathin film quality. We observe an increase of $q\Phi_2$ up to 0.26 eV for 12 Å thick ALD Al_2O_3 on GaAs. The data $q\Phi_2$ obtained from constant electric field or constant gate bias are almost the same for 15 Å–30 Å samples, since the J_L versus $1/T$ slope is not dependent on electric fields in oxide films as shown in Fig. 3.

4. Conclusion

In summary, we have systematically studied current-transport of ultrathin Al_2O_3 dielectrics on GaAs grown by ALD as a function of oxide thickness, ambient temperature, and electric field. The leakage current in ultrathin Al_2O_3 on GaAs, comparable to or even lower than that of state-of-the-art SiO_2 on Si, indicates the extremely high quality of Al_2O_3 on GaAs. The ALD Al_2O_3 film grows remarkably well and is an excellent choice for an insulating or protective layer on a wide variety of device applications. The hopping of thermally excited electrons inside oxide is identified as the major mechanism for the current-transport in ultrathin Al_2O_3 on GaAs at temperatures ranging from 133 K to 475 K. We propose the use of thermal-activation energy in characterizing the quality of ultrathin oxides.

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