Current transport and maximum dielectric strength of atomic-layer-deposited ultrathin Al_2O_3 on GaAs

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Current-voltage characteristics have been measured for an ultrathin atomic-layer-deposited Al_2O_3 on GaAs as a function of film thickness, ambient temperature, and electric field. Current transport measurements indicate direct tunneling for 12–25 Å ultrathin films and typical Frenkel-Poole emission for 50–60 Å thick films. The maximum dielectric strength, which is of considerable importance for metal-oxide-semiconductor device applications, is studied thoroughly in this letter. The square root of the maximum dielectric strength is found to be roughly reversely proportional to the temperature from 500 to 300 K, and becomes constant below 200 K. The enhancement in the dielectric field strength observed from 300 to 200 K for the ultrathin insulating films can be adequately described using classical models. © *2007 American Institute of Physics*.
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In order to further drive complementary metal-oxide-semiconductor (CMOS) integration beyond the 22 nm node, novel channel materials and device structures must be developed to improve its functional density, speed, and power dissipation. One emerging research field involves the use of III-V compound semiconductor materials as conduction channels to replace traditional Si or strained Si.[1] These high mobility materials could be integrated with novel high-*k* dielectrics and heterogeneously built on silicon or silicon on insulator. The research in III-V materials and devices for logic applications represents a great opportunity but also a significant challenge, since the heterogeneous integration of III-V compound semiconductors on Si and the growth of high-quality gate dielectrics on III-V are both "historically" difficult problems.[2,3]

Atomic layer deposition (ALD) is an ultrathin-film deposition technique based on sequences of self-limiting surface reactions, which enables thickness control on the atomic scale. The recent development of high-quality ALD gate dielectrics on Si or Ge justifies some optimism regarding the integration of deposited oxides on III-V compound semiconductors. We have applied ALD to grow Al_2O_3 gate dielectrics on III-V compound semiconductors and demonstrated high-performance depletion-mode MOS field-effect transistors.[4–6] Current research thrusts are focused on III-V CMOS technology for large-scale integration or digital applications. This requires not only improved oxide/semiconductor interface properties but also high-*k* gate dielectrics with further scalability to sub-1.0 nm effective inversion gate-oxide thicknesses. Nevertheless, the current transport and maximum dielectric strength studies of ultrathin high-*k* oxides on GaAs are of utmost importance. Al_2O_3 is a widely used insulating material for gate dielectrics, tunneling barriers and protection coatings due to its excellent dielectric properties, strong adhesion to dissimilar materials, and its exceptional thermal and chemical stabilities. Al_2O_3 has a high band gap (~9 eV), a high breakdown electric field (5–30 MV/cm),[7] a high permittivity (8.6–10), high thermal stability (up to at least 1000 °C), and remains amorphous under typical processing conditions. The leakage current observed in ultrathin Al_2O_3 on GaAs is equivalent to or lower than that of the state-of-the-art SiO_2 on Si. The breakdown electric field of Al_2O_3 films thicker than 50 Å can be up to ~10 MV/cm; this value is near the bulk breakdown electric field for SiO_2. A significant enhancement in the breakdown electric field (up to ~30 MV/cm) has been observed for smaller film thicknesses (12 Å).[7] In this letter, we report detailed maximum dielectric strength studies of ultrathin ALD Al_2O_3 dielectrics on GaAs. Based on our findings, the low-temperature breakdown electric field in 12 Å thick Al_2O_3 can be as high as 60 MV/cm.

2 in. Si-doped GaAs wafers with a doping concentration of $(6-8)\times 10^{17}/cm^3$ were initially pretreated with a dilute HF solution to remove the native oxide present on its surface. The wafers were then transferred immediately to an ASM Pulsar2000™ ALD module to grow the Al_2O_3 films. The films were grown using alternating pulses of $Al(CH_3)_3$ (the aluminum precursor) and H_2O (the oxygen precursor) in the presence of N_2 carrier gas flow. An excess of each precursor was supplied alternatively to saturate the surface sites and to ensure self-limiting film growth. The number of ALD cycles was varied to modulate the thickness of Al_2O_3 films. Various Al_2O_3 oxide layers of thicknesses of 12, 15, 20, 25, 30, 40, 50, and 60 Å were deposited at a substrate temperature of 300 °C. All of the deposited films were amorphous, making them favorable to be used as a gate dielectric. Following the deposition, the films were annealed at 600 °C with oxygen gas in a rapid thermal annealing chamber. A 1000 Å thick Au film was then deposited on the backside of the GaAs wafer to reduce the contact resistance between the wafer and electrical probes. The oxide leakage current was measured by 3000 Å of Au, which served as the top electrode of the capacitor.

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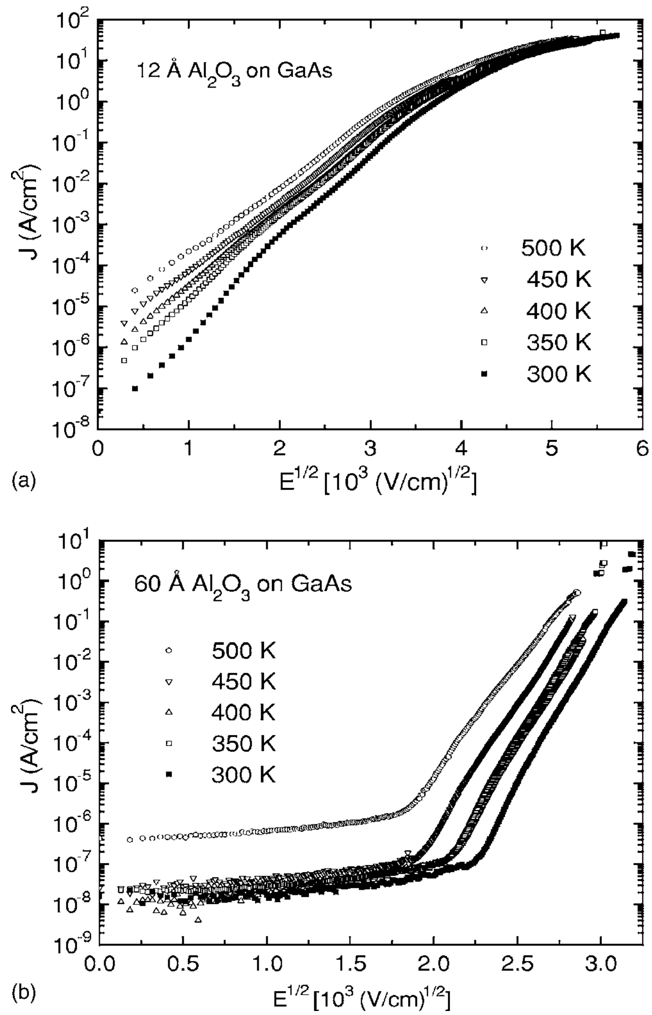

FIG. 1. (a) Measured leakage current density J vs square root of electric field E for 12 Å thick ALD Al_2O_3 films on GaAs at five different temperatures (300 K $\leq T \leq$ 500 K). (b) The similar measurement performed at 60 Å thick ALD Al_2O_3 films on GaAs.

Figure 1 shows the leakage current density (J) versus the square root of the electric field (E) on 12 and 60 Å thick Al_2O_3 films at five different ambient temperatures. A voltage bias was applied on the metal electrodes with respect to the grounded GaAs substrate. The Al_2O_3 dielectric films are highly electrically insulating. A very low leakage current density ($\sim 10^{-9}$–10^{-8} A/cm^2) is exhibited near zero bias at the limit of instrumentation. Figs. 1(a) and 1(b) show significantly different features. Assuming that the dielectric constant of Al_2O_3 is 8.6 without any interfacial layer, the 12 Å Al_2O_3 film with an equivalent oxide thickness of only 5.4 Å shows a well-behaved direct tunneling characteristic. Dielectric breakdown transpires at an electric field near 30 MV/cm at 300 K. Compared to the state-of-the-art SiO_2 on Si using a polysilicon gate, the leakage current density of Al_2O_3 on GaAs is equivalent to or even one order of magnitude lower at a similar bias range.[7] The plot also shows a slight increase in current density with increasing temperature; this is unequivocal to a pure tunneling mechanism, which lacks temperature dependence. Figure 1(b) indicates typical Frenkel-Poole emission features. It has been pointed out by O'Dwyer[8] that a linear dependence of log(J) vs $E^{1/2}$ quite accurately over several decades does not necessarily imply a Frenkel-Poole emission since the plot of log(J) vs $E^{1/2}$ for

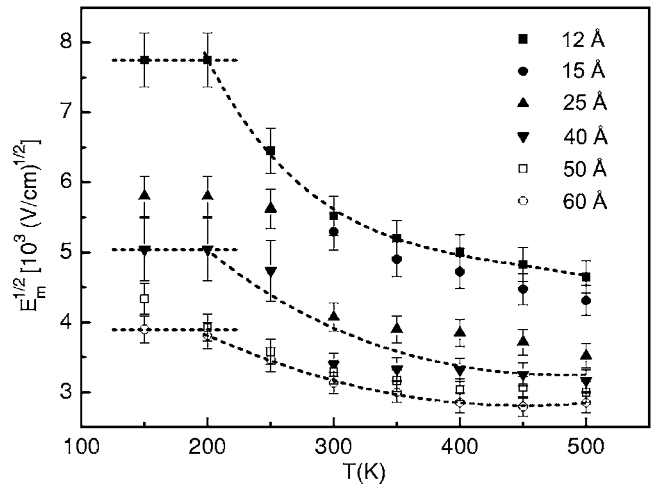

FIG. 2. Square root of the maximum dielectric strength E_m vs ambient temperature T for six different thickness ALD Al_2O_3 films on GaAs. The dashed lines are calculated via Eqs. (1)–(3) on film thicknesses of 12, 40, and 60 Å using the experimental data except for C_1/Γ as a fitting parameter.

tunneling or Fowler-Nordheim cold emission is also found to be a straight line over many decades of current density. The dynamic dielectric constant (ε_d), obtained from the slopes of curves at high fields and high temperatures in Fig. 1(b), is found to be on the same order of magnitude as the static dielectric constant for Al_2O_3. The value obtained from the slopes of curves in Fig. 1(a) is one order of magnitude higher than the static value. This result is of paramount importance to confirm that the dynamic dielectric constant is self-consistent and the dominant transport mechanism is indeed Frenkel-Poole emission. As the ramp voltage or electric field increases, the conduction current or current density increases accordingly. Eventually, the electric field reaches a maximum value, beyond which destructive breakdown occurs. The above maximum voltage or breakdown voltage normalized to the film thickness is defined as the maximum dielectric strength (E_m). The difference between the metal work function and GaAs affinity is considered to determine the breakdown voltage across the insulating film. We use ellipsometry, high-resolution transmission electron microscopy, and tunneling currents to calibrate the physical thickness of these ALD films. The results were compared to the predetermined target thicknesses based on our selected number of ALD reaction cycles (see Fig. 3 in Ref. 7). A clear 1:1 linear dependency is obtained for film thicknesses larger than 15 Å with an error of less than 5%. Some evidence for accelerated initial Al_2O_3 growth on HF-pretreated GaAs surface, reported in Ref. 9, is also observed in our experiments. The error bars are given on E_m in Fig. 2, considering a 5%–20% uncertainty on film thicknesses and the near Gaussian distribution of breakdown voltages measured on assembly of 10–20 devices at the same film thickness.

Following Klein and Gafni's work, assuming that E_m is limited by the thermal instability of the structure[10] and Sze's classical model on Si_3N_4,[11] an approximate expression for the maximum dielectric strength as a function of the ambient temperature is

$$E_m \approx (\pi\varepsilon_0\varepsilon_d/q)[\Phi_1 - CT]^2, \quad (1)$$

where

$$C \equiv (k/q)\ln[q(\Phi_1 - aE_m^{1/2})C_1E_m^2Ad/\Gamma kT^2], \quad (2)$$

which is a slowly varying function of T and E_m. Φ_1 is the barrier height for Frenkel-Poole emission, ε_0 is the permittivity of free space, ε_d is the dynamic dielectric constant, q is the charge of electrons, $a \equiv (q/\pi\varepsilon_0\varepsilon_d)^{1/2}$, C_1 is the proportionality constant for Frenkel-Poole emission dependant on density of the trapping centers, A is the area of the structure, d is the thickness of the film, and Γ is the thermal conductance. At low temperatures, the longitudinal-phonon energy $h\nu \gg kT$, E_m becomes the intrinsic dielectric strength independent of T as

$$E_m(T) \approx E(0). \quad (3)$$

The plot of $E_m^{1/2}$ vs T, as shown in Fig. 2, verifies that the maximum dielectric strength of ultrathin ALD films on GaAs could be *surprisingly* depicted by the classical model, Eqs. (1)–(3), developed for thick insulating films.[10,11] The value of E_m at a given temperature is virtually independent of film thickness for thick films. The bulk value for ALD Al_2O_3 on GaAs at room temperature is around 10 MV/cm as shown in Fig. 2 for 60 Å film. The bulk value of E_m at low temperatures becomes independent of the temperature and approaches a value of ~15 MV/cm; this is predicted by Eq. (3). The value of E_m is strongly dependent on the film thickness for values of 40 Å or less due to the well-known E_m enhancement for the ultrathin insulating films.[11] Based on our findings, this enhancement becomes significant once the film thickness approaches 25 Å. The value of E_m increases to 30 MV/cm at room temperature and 60 MV/cm at low temperatures for 12 Å thick Al_2O_3 on GaAs. The "anomalous" or rapid increase of E_m with the decrease of temperature observed only for ultrathin films can be expected since E_m is proportional to $[\Phi_1\text{-}CT]^2$ based on Eq. (1). C is a "constant" as a slowly varying function of E_m and T, which has the largest value for the thinnest film, as described in Eq. (2). The dashed lines are calculated curves on three representative film thicknesses using Eqs. (1)–(3), where C_1/Γ is a fitting parameter for the appropriated regions.

In summary, we have systematically studied current-transport characteristics in conjunction with the maximum dielectric strength of ultrathin atomic-layer-deposited Al_2O_3 dielectrics grown on GaAs as a function of oxide thickness, ambient temperature, and electric field strength. The Al_2O_3 films were grown remarkably well on GaAs using ALD. This makes them an excellent choice for its use in passivation layers or dielectrics for III-V MOS devices. Current transport measurements indicate direct tunneling for 12–25 Å ultrathin films and typical Frenkel-Poole emission for 50–60 Å thick films. The maximum dielectric strength of 12 Å ALD Al_2O_3 on GaAs is ~30 MV/cm at room temperature and reaches ~60 MV/cm at low temperatures.

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[1]T. Ashely, A. R. Barnes, L. Buckle, S. Datta, A. B. Dean, M. T. Emeny, M. Fearn, D. G. Hayes, K. P. Hilton, R. Jefferies, T. Martin, K. J. Nash, T. J. Phillips, W. H. A. Tang, P. J. Wilding, and R. Chau, Proceedings of the Seventh International Conference Solid-State and Integration-Circuit Technology, 2004 (unpublished), p. 2253.
[2]T. Mimura and M. Fukuta, IEEE Trans. Electron Devices **ED-27**, 1147 (1980), and references therein.
[3]*Physics and Chemistry of III-V Compound Semiconductor Interfaces*, edited by C. W. Wilmsen (Plenum, New York, 1985), p. 403 and references therein.
[4]P. D. Ye, G. D. Wilk, J. Kwo, B. Yang, H.-J. L. Gossmann, M. Frei, S. N. G. Chu, J. P. Mannaerts, M. Sergent, M. Hong, K. Ng, and J. Bude, IEEE Electron Devices Letters **24**, 209 (2003).
[5]P. D. Ye, G. D. Wilk, B. Yang, J. Kwo, H.-J. L. Gossmann, S. N. G. Chu, S. Nakahara, H.-J. L. Gossmann, J. P. Mannaerts, M. Sergent, M. Hong, K. Ng, and J. Bude, Appl. Phys. Lett. **83**, 180 (2003).
[6]P. D. Ye, G. D. Wilk, B. Yang, J. Kwo, H.-J. L. Gossmann, M. Hong, K. Ng, and J. Bude, Appl. Phys. Lett. **84**, 434 (2004).
[7]H. C. Lin, P. D. Ye, and G. D. Wilk, Appl. Phys. Lett. **87**, 182904 (2005).
[8]J. J. O'Dwyer, J. Appl. Phys. **37**, 599 (1966).
[9]M. M. Frank, D. G. Wilk, D. Starodub, T. Gustafsson, E. Garfunkel, Y. J. Chabal, J. Grazul, and D. A. Muller, Appl. Phys. Lett. **86**, 152904 (2005).
[10]N. Klein and H. Gafni, IEEE Trans. Electron Devices **ED-13**, 281 (1966).
[11]S. M. Sze, J. Appl. Phys. **38**, 2951 (1966).