# Leakage current and breakdown electric-field studies on ultrathin atomic-layer-deposited $Al_2O_3$ on GaAs

H. C. Lin and P. D. Ye[a)]
*School of Electrical and Computer Engineering, Purdue University, West Lafayette, Indiana 47907*

G. D. Wilk
*Advanced Semiconductor Materials (ASM) America, 3440 East University Drive, Phoenix, Arizona 85034*

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Atomic-layer deposition (ALD) provides a unique opportunity to integrate high-quality gate dielectrics on III-V compound semiconductors. We report detailed leakage current and breakdown electric-field characteristics 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 state-of-the-art $SiO_2$ on Si, not counting the high-*k* dielectric properties for $Al_2O_3$. A Fowler-Nordheim tunneling analysis on the $GaAs/Al_2O_3$ barrier height is also presented. The breakdown electric field of $Al_2O_3$ is measured as high as 10 MV/cm as a bulk property. A significant enhancement on breakdown electric field up to 30 MV/cm is observed as the film thickness approaches to 1 nm. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2120904]

$Al_2O_3$ 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 stabilities. $Al_2O_3$ has a high band gap (~9 eV), a high breakdown electric field (5–10 MV/cm), a high permittivity (8.6–10), 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. ALD is an ultra-thin-film deposition technique based on sequences of self-limiting surface reactions enabling thickness control on atomic scale. The ALD high-*k* materials including $Al_2O_3$ are the leading candidates to substitute $SiO_2$ for sub-100 nm Si complimentary metal-oxide-semiconductor field-effect transistor (MOSFET) applications.[1] ALD also provides unique opportunity to integrate high-quality gate dielectrics on non-Si semiconductor materials. We have applied the ALD grown high-*k* gate dielectrics on high-mobility III-V compound semiconductors and demonstrated GaAs and GaN MOSFETs with excellent device performance.[2–5] The quality of ultrathin $Al_2O_3$ on GaAs is of great importance for exploring the ultimate ultrahigh-speed MOSFETs or terahertz MOSFETs which combine the following three features: (1) high-*k* dielectrics (2) high-mobility carrier channels, and (3) ultrashort gate lengths below 100 nm.

In this Letter, we report detailed leakage current and breakdown electric-field characteristics 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, not counting the high-*k* dielectric properties for $Al_2O_3$, which is more than a factor of 2 higher compared to $SiO_2$. Through Fowler-Nordheim (FN) tunneling analysis, the $GaAs/Al_2O_3$ barrier height is determined. 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 ALD $Al_2O_3$. A significant enhancement on breakdown electric field up to 30 MV/cm is observed as the film thickness approaches to 10 Å. The capability to deposit high-quality ultrathin insulating films on dissimilar materials by ALD opens the way to explore novel device concepts away from the traditional Si MOSFETs.

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 to eliminate the interfacial layer sometimes existing at the $Al_2O_3/GaAs$ interface. The wafers were transferred immediately to an ASM Pulsar2000™ 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, and 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 Letter 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.

The $Al_2O_3$ dielectric films are highly electrically insulating, showing very low leakage current density of $\sim 10^{-10}-10^{-9}$ A/cm$^2$ at zero bias, as shown in Fig. 1. This could do with the fact that Al is electropositive +3 and has a strong affinity to oxygen. We measured the dependence of the leakage current density ($J_L$) on the applied potential on the capacitor ($V_g$) for a set of ALD $Al_2O_3$ samples with the oxide thickness systematically reduced from 50 to 12 Å. The

[a)]Author to whom correspondence should be addressed; electronic mail: yep@purdue.edu

 

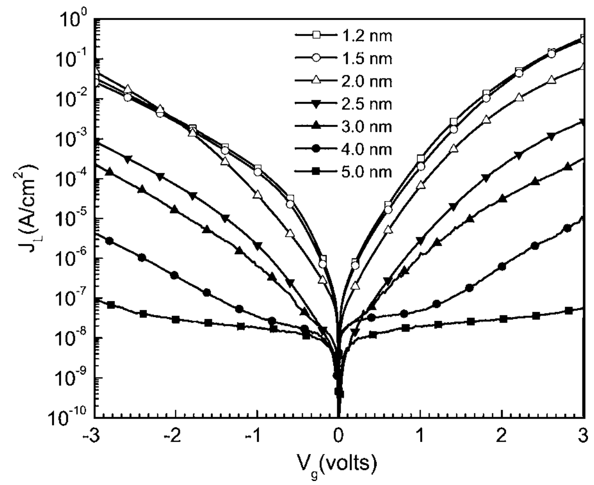


FIG. 1. Leakage current density $J_L$ vs gate bias $V_g$ for ALD $Al_2O_3$ films on GaAs with different film thickness from 12 to 50 Å.

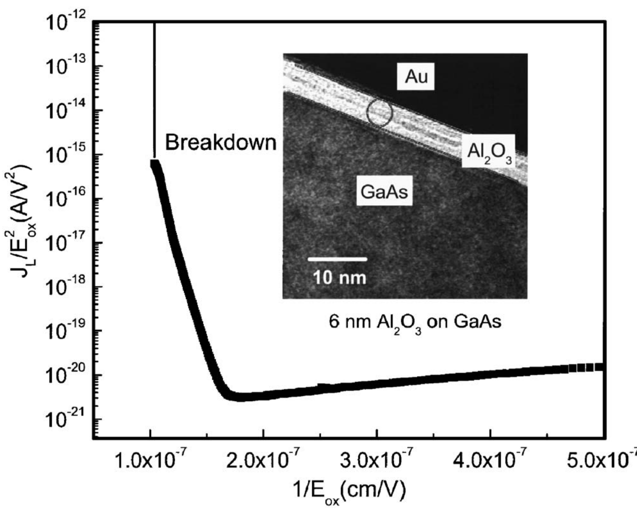


FIG. 2. Fowler-Nordheim plot ($J_L/E_{ox}^2$ vs $1/E_{ox}$) of the $I$-$V$ data for a 60-Å-thick $Al_2O_3$ ALD film on GaAs. Inset: high-resolution TEM image of this sample.

positive bias means that the metal electrode is positive with respective to GaAs. The plot shows a decrease in current density with increasing film thickness in general. Direct tunneling current is observed for film thickness $\leqslant$30 Å, while film with thickness $\geqslant$50 Å shows no significant direct tunneling. The 12 Å $Al_2O_3$ with the equivalent oxide thickness of only 4.7 Å still shows well-behaved direct tunneling characteristic and does not break down at ±3 V bias. Compared to the state-of-the-art $SiO_2$ on Si, the leakage current density of $Al_2O_3$ on GaAs is one order of magnitude lower. The low electrical leakage even for films as thin as 12 Å suggests that ALD supplies a new technology to form unprecedented high-quality insulating films on various substrates.

The rise in leakage current observed in the $J_L$-$V_g$, as shown in Fig. 1, at higher applied bias is consistent with FN tunneling. The electron tunneling through a triangular barrier for this type of field-assisted tunneling is described as

$$J=\alpha E_{ox}{}^2 \exp(-\beta/E_{ox}), \quad (1)$$

where

$$\alpha = 1.54 \times 10^{-6}/m^* \Phi_B$$

and

$$\beta = 6.83 \times 10^7 (m^*)^{1/2} (\Phi_B)^{3/2}. \quad (2)$$

$m^*$ is the effective electron mass in the insulator and $\Phi_B$ is the barrier height. Figure 2 shows a plot of $J/E_{ox}{}^2$ vs $1/E_{ox}$ resulting from $I$-$V$ measurement of a 60-Å-thick $Al_2O_3$ film as shown by a high-resolution transmission electron microscopy (TEM) image in the inset of Fig. 2. The negative slope of $-\beta$, before its breakdown at ~10 MV/cm, can be used to calculate the $Al_2O_3$/GaAs barrier height, which is an important parameter for device design. Using $m^*=0.23$ for $Al_2O_3$ and Fig. 2, the GaAs/$Al_2O_3$ barrier height $\Phi_B$ is ~3.2 eV, which is higher than the Si/$Al_2O_3$ barrier height of 2.6 eV determined by the similar method.[6]

Breakdown electric field ($E_{BR}$) is an important material parameter to evaluate the strength of the insulating layer. $E_{BR}$ is defined as $V_{BR}$ divided by $T_{ox}$, where $V_{BR}$ is the breakdown electric voltage across the insulating layer and $T_{ox}$ is the physical thickness of the insulating layer. Between 16–25 breakdown measurements were performed on different devices on each thickness ranging from 12 to 60 Å. The distribution of the $V_{BR}$ is narrow but existing. By assuming that the $V_{BR}$ follows the Gaussian distribution, we find its average standard-deviation-to-mean ratio to be 7.6%. We choose the fitted peak value as the final $V_{BR}$ after taking account the 0.4 eV Schottky barrier height between Au and GaAs at the backside, and 0.3 eV potential difference between Au work function and GaAs affinity to vacuum. To measure the exact physical thickness of an ultrathin insulating film is also challenging, in particular, as the film thickness approaches 10 Å. We use ellipsometry, high-resolution TEM, and tunneling currents to calibrate the physical thickness of these ALD films previously determined by counting the number of ALD reaction cycles, as shown in Fig. 3. A good 1:1 linear dependence is obtained as the film thickness larger than 15 Å with the error less than 5%. More deviation could occur as the film thickness approaches 10 Å.

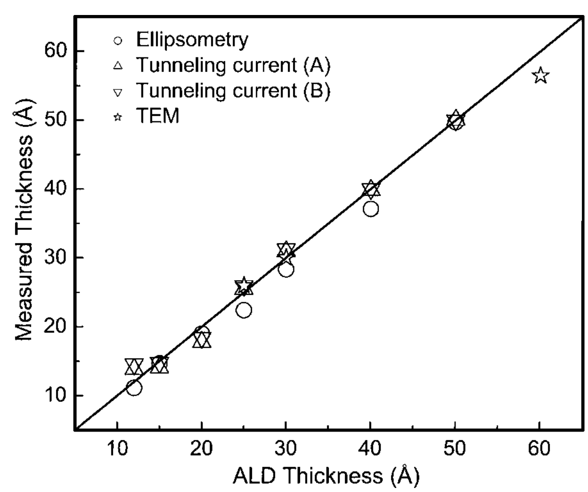


FIG. 3. The measured film thickness by ellipsometry, tunneling current, and high-resolution TEM vs the film thickness determined by the ALD growth or the number of reaction cycles. The measured thickness (upper triangles) of "tunneling current (A)" is determined by the linear fitting of all data points of $\ln(J_L)$ vs $T_{ox}$, while the thickness (down triangles) of "tunneling current (B)" is determined by the linear line with two fixed points of 50 and 60 Å. Here, we assume that the thickness for 50 and 60 Å determined by ALD growth is accurate.

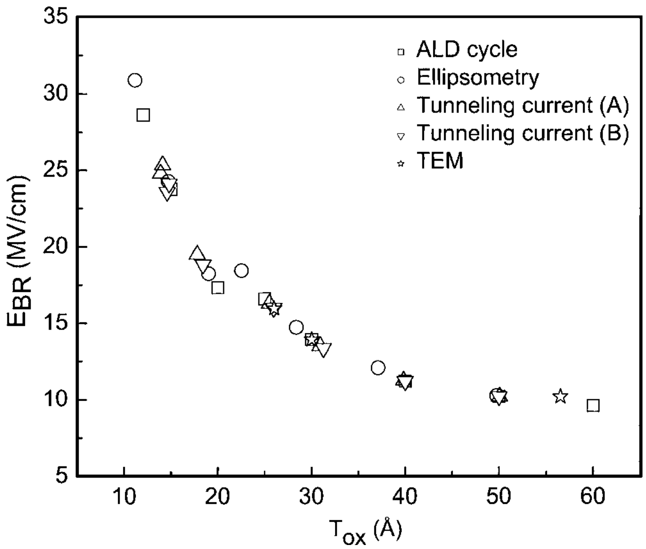


FIG. 4. The breakdown electric fields vs different thicknesses of the ALD films. The different signs represent the thickness determined by different methods.

Figure 4 shows the summary plot of $E_{BR}$ vs $T_{ox}$ determined by various methods. The electrical properties of ALD $Al_2O_3$ films have been investigated by several research groups.[6–13] But most of these studies were performed on films on the order of ~1000 Å thick and the films grown on Si substrates. What we observed 10 MV/cm $E_{BR}$ for ALD $Al_2O_3$ films with the thickness of between 50–60 Å is slightly higher than the reported 7–8 MV/cm bulk $E_{BR}$. The higher breakdown electric field indicates the possibility of the higher quality of ALD films grown by commercial ALD reactors in our experiments. It could be also due to the remnant of the $E_{BR}$ enhancement of ultrathin films. A huge $E_{BR}$ enhancement is observed in Fig. 4 as the film thickness is thinner than 40 Å. The $E_{BR}$ for the 12 Å film is more than a factor of 3 larger than the bulk value. It could be explained that the relative large leakage current density in an ultrathin oxide prevents the occurrence of hard breakdown of oxide film at a low electric field. The high breakdown field for ultrathin oxide on GaAs provides great opportunity for reducing the gate oxide thickness. The superb electrical characteristics of ALD films on GaAs demonstrate the potential to scale down the gate length of GaAs MOSFET below 100 nm with reliable ultrathin high-*k* oxide layers as dielectrics.

In summary, we have systematically studied leakage current and breakdown electric-field characteristics of ultrathin $Al_2O_3$ dielectrics on GaAs grown by ALD. 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. A significant enhancement on breakdown electric field up to 30 MV/cm opens the way to explore other novel device concepts and exotic physics phenomena, which requires extremely high electric field on insulating layers.

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[1]G. D. Wilk, R. M. Wallace, and J. M. Anthony, J. Appl. Phys. **89**, 5243 (2001).
[2]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 Device Lett. **24**, 209 (2003).
[3]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).
[4]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).
[5]P. D. Ye, B. Yang, K. Ng, J. Bude, G. D. Wilk, S. Halder, and J. C. M. Hwang, Appl. Phys. Lett. **86**, 063501 (2005).
[6]M. D. Groner, J. W. Elam, F. H. Fabreguette, and S. M. George, Thin Solid Films **413**, 186 (2002).
[7]W. S. Yang, Y. K. Kim, S. Y. Yang, J. H. Choi, H. S. Park, S. I. Lee, and J. B. Yoo, Surf. Coat. Technol. **131**, 79 (2000).
[8]G. S. Higashi and C. G. Fleming, Appl. Phys. Lett. **55**, 1963 (1989).
[9]J. Fan, K. Sugioka, and K. Toyoda, Jpn. J. Appl. Phys., Part 2 **30**, L1139 (1991).
[10]H. Kattelus, M. Ylilammi, J. Saarilahti, J. Antson, and S. Lindfors, Thin Solid Films **225**, 296 (1993).
[11]K. Kukli, M. Ritala, M. Leskela, and J. Jokinene, J. Vac. Sci. Technol. A **15**, 2214 (1997).
[12]P. Ericsson, S. Bengtsson, and J. Skarp, Microelectron. Eng. **36**, 91 (1997).
[13]V. E. Drozd, A. P. Baraban, and I. O. Nikiforova, Appl. Surf. Sci. **82/83**, 583 (1994).