ALD HfO_2, Al_2O_3, and PECVD Si_3N_4 as MIM Capacitor Dielectric for GaAs HBT Technology

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Abstract

Characterization was performed on 60 nm +/- 3 nm films of atomic layer deposition (ALD) hafnium dioxide (HfO_2) and aluminum oxide (Al_2O_3), and plasma-enhanced chemical vapor deposition (PECVD) silicon nitride (Si_3N_4) as MIM capacitor dielectric for GaAs HBT technology. The capacitance density of MIM capacitor with ALD HfO_2 (2.73 fF/μm^2) and Al_2O_3 (1.55 fF/μm^2) is significantly higher than that with PECVD Si_3N_4 (0.92 fF/μm^2). However, the breakdown voltage of the ALD HfO_2 (34 V) and Al_2O_3 (41 V) is lower than that of PECVD Si_3N_4 (73 V). Additionally, the PECVD Si_3N_4 leakage current density is significantly lower than that of ALD HfO_2 and Al_2O_3. As the temperature was increased from 25°C to 150°C, the leakage current of all films increased. The capacitance of ALD Al_2O_3 and HfO_2 films was observed to change slightly, when the applied voltage was varied from -5 V to +5 V. No significant change in capacitance was seen for all three films, when the frequency was increased from 1 kHz to 1 MHz. The extracted quality factor at 1 GHz of the MIM capacitor with ALD HfO_2 and Al_2O_3 is lower than that with PECVD Si_3N_4 by about 50%. These results show that the three films have different advantages, are suitable for, and can be used as MIM capacitor dielectric for GaAs HBT technology. The capacitor dielectric can be selected based on the specific electrical requirements, application, and operating conditions of the GaAs IC design.

INTRODUCTION

Due to the increasing demand for capacity and increasing complexity and functionality of devices in IC designs, the die size in semiconductor wafer manufacturing must be reduced. One of the methods to reduce the die size is to increase the capacitance density of the MIM capacitor, which is a key passive component in GaAs RF IC designs. Excluding the areas of the bond pad and scribe streets, MIM capacitors could consume up to 35% of the die area in many GaAs circuit designs [1,2]. A higher capacitance density capacitor will allow the reduction of the capacitor area, resulting in die size reduction, and will also allow the integration of additional capacitors on to the chip, including off-chip capacitors, thereby reducing the bill-of-materials in a multi-chip module.

In addition to high capacitance density, the MIM capacitor in GaAs technology typically is also required to have high breakdown voltage, low leakage current, and high quality factor. The operating voltage of many GaAs HBT RF designs, such as power amplifiers, is high, and the transistor output voltage swings can be $\geq$20 V. Furthermore, the breakdown voltage requirements of capacitors used in one design may be different from those in others and depend on the application [1-4]. Designs for high power infrastructure and base station applications typically require capacitors with higher breakdown voltage than those for cellular and wireless applications.

The most widely used MIM capacitor dielectric in GaAs technology is PECVD Si_3N_4 [1,5-11]. This Si_3N_4 film is known to have relatively good electrical, physical, and chemical characteristics. Furthermore, it can be deposited at a temperature of $\leq$300°C, which is required in GaAs technology, due to the degradation of typically used GaAs contact metal materials at higher temperatures [1,3,10-12]. However, PECVD Si_3N_4 has a dielectric constant κ of only 6-7, resulting in a relatively low capacitance density.

Recently, ALD method has been used to deposit high quality thin films for many applications in semiconductor technology, including thin high κ dielectric materials [2,4,13-16]. This ALD method can produce various films that are highly conformal with excellent thickness and composition control. Furthermore, ALD films can be deposited at low temperatures, making this film very attractive for use in GaAs technology. In previous studies, we have developed high density MIM capacitors using ALD Al_2O_3 and HfO_2 as capacitor dielectric [2,4]. In this study, we have further evaluated and characterized ALD HfO_2 and Al_2O_3 films as MIM capacitor dielectric for GaAs HBT technology, and compared the results to those of PECVD Si_3N_4.

EXPERIMENTAL

The ALD Al_2O_3 and HfO_2 films were deposited using a Picosun Advanced SUNALE P-300 reactor. The precursors used for the deposition of the ALD Al_2O_3 were trimethyl aluminum (TMA), water, and O_3, while those used for deposition of the ALD HfO_2 were tetrakisethylmethylamino hafnium (TEMAH), water, and O_3. The deposition temperature of the ALD Al_2O_3 and HfO_2 was 300ºC and 230ºC, respectively. The PECVD Si_3N_4

film was deposited at 300ºC in a multi-station sequential system (Novellus Concept-1). The gases used for the Si_3N_4 deposition were SiH_4, NH_3, and N_2. The deposition thickness target of both films was 60 nm +/- 3 nm. The films were deposited on 6" GaAs wafers, including device and bare test wafers. The device wafers were fabricated using GaAs HBT technology, which includes the fabrication of multi-epitaxial structures, metal interconnections, and various active and passive devices, including transistors and MIM capacitors. The MIM capacitor on the GaAs HBT wafers includes the capacitor dielectric insulator, sandwiched between the bottom and top evaporated metal electrodes. The bottom metal electrode consists of 1 μm thick Au with a thin Ti adhesion layer on top, while the top metal electrode consists of 2 μm thick Au with a thin Ti layer at the bottom.

A FilmTek 2000 reflectometer and Rudolph FE-VII ellipsometer were used to measure the thickness and refractive index of the HfO_2, Al_2O_3, and Si_3N_4 films. Focus-Ion Beam/Scanning Electron Microscopy (FIB/SEM) analysis was performed using a FEI Nova 600i instrument to evaluate the fabricated MIM capacitor structures, including the conformality of the films. Electrical characterization was performed by collecting both current-voltage (I-V) and capacitance-voltage (C-V) measurements using an Agilent B1500A semiconductor device analyzer. The applied voltage for I-V characterization ranges from 0 to 80 V. Both the I-V and C-V measurements were performed on MIM capacitors with different areas, ranging from 100 to 10,000 μm^2, and at the temperatures of 25ºC and 150ºC. Capacitance characterization was also performed at different frequencies of 1 kHz and 1 MHz, and at different applied voltages, ranging from -5 V to +5 V. For all I-V measurements, the ground voltage is applied to the bottom metal electrode, while the bias voltage is applied to the top metal electrode. The quality factor of the capacitors was extracted from S-parameter measurements performed using an Agilent 8510C vector network analyzer.

RESULTS AND DISCUSSION

The thickness of the ALD Al_2O_3, ALD HfO_2, and PECVD Si_3N_4 films was measured to be 59 nm, 62 nm, and 63 nm, respectively. The measured refractive index of Al_2O_3, HfO_2, and Si_3N_4 films was 1.654, 1.973, and 1.875, respectively. Figure 1 shows the FIB/SEM image of a MIM capacitor manufactured using GaAs HBT technology, connected to the transistor, comprising the base, emitter, and collector. Figure 2 (a), (b), and (c) shows the images of the MIM capacitor with ALD HfO_2 and ALD Al_2O_3, and PECVD Si_3N_4 thin dielectric films, sandwiched between the top and bottom metal electrodes. It can be seen that all three dielectric films show good conformality, when deposited on this rough, underlying evaporated metal surface. The good conformality of these films will lead to more uniform thickness across the MIM capacitor on the wafers, resulting in more uniform capacitance, leakage current, and breakdown characteristics of the capacitor across the GaAs wafer.

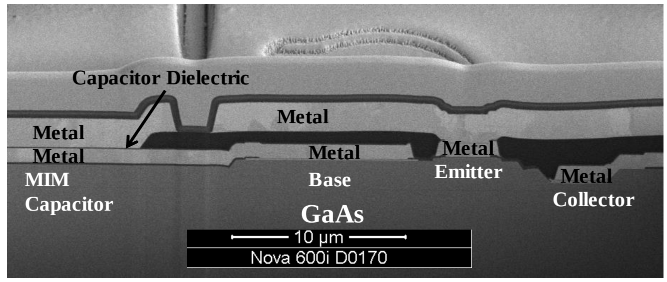

Figure 1. MIM capacitor connected to the transistor and manufactured using GaAs HBT technology.

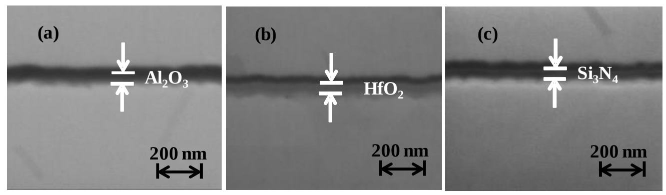

Figure 2. MIM capacitor with (a) ALD Al_2O_3, (b) ALD HfO_2, and (c) PECVD Si_3N_4 as capacitor dielectric.

Figure 3 shows the capacitance density and dielectric constant obtained from the MIM capacitor with 59 nm ALD Al_2O_3, 62 nm ALD HfO_2, and 63 nm PECVD Si_3N_4 dielectric films. As can be seen, the ALD HfO_2 has a capacitance density of 2.73 fF/μm^2, which is 76% higher than that of ALD Al_2O_3 (with a capacitance density of 1.55 fF/μm^2), and 197% higher than that of PECVD Si_3N_4 (with a capacitance density of 0.92 fF/μm^2). The dielectric constant of these HfO_2, Al_2O_3 and Si_3N_4 films, calculated using simple parallel plate model, was 19.1, 10.3 and 6.5, respectively.

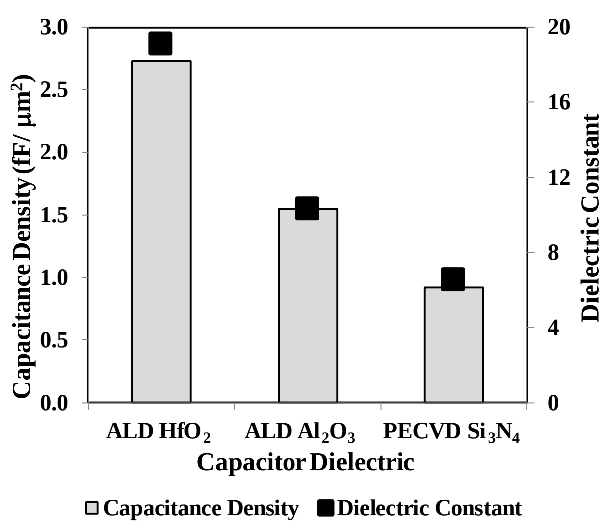

Figure 3. Capacitance density of MIM capacitor with, and dielectric constant of 59 nm ALD HfO_2, 62 nm ALD Al_2O_3, and 63 nm PECVD Si_3N_4.

Since most GaAs devices may be operating at varying conditions, it is important to investigate the electrical characteristics at different temperatures and frequencies. Figures

4 and 5 show the capacitance of MIM capacitor with an area of 4055 μm^2, as the applied voltage was varied from -5 V to +5V, and at the temperatures of 25°C to 150°C and at the frequencies of 1 kHz and 1 MHz. As can be seen, the capacitance of the MIM capacitor with these films did not vary significantly when the applied voltage was varied from -5 to 5 V. However, an increase in temperature from 25°C to 150°C resulted in a slight capacitance increase of about 2.5-2.9% for MIM capacitor with ALD HfO_2 and Al_2O_3. No significant capacitance change was observed with PECVD Si_3N_4. The data also show that no change in capacitance was observed, when the frequency was increased from 1 kHz to 1 MHz for all three films.

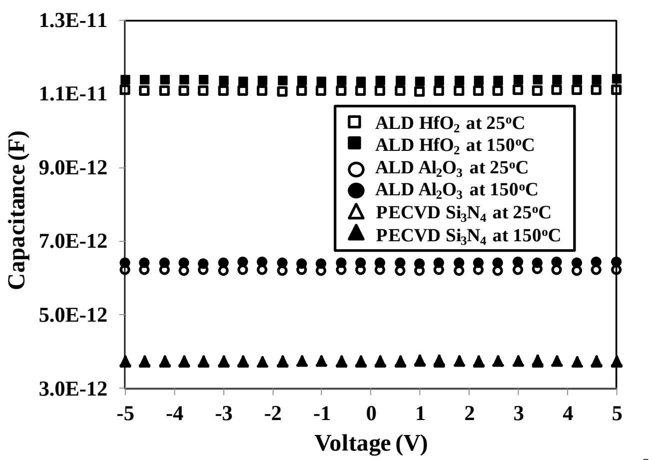

Figure 4. The capacitance of MIM capacitor with an area of 4055 μm^2, as a function of applied voltage and at temperature of 25°C and 150°C. Some of the data points obtained at 25°C and 150°C overlapped each other.

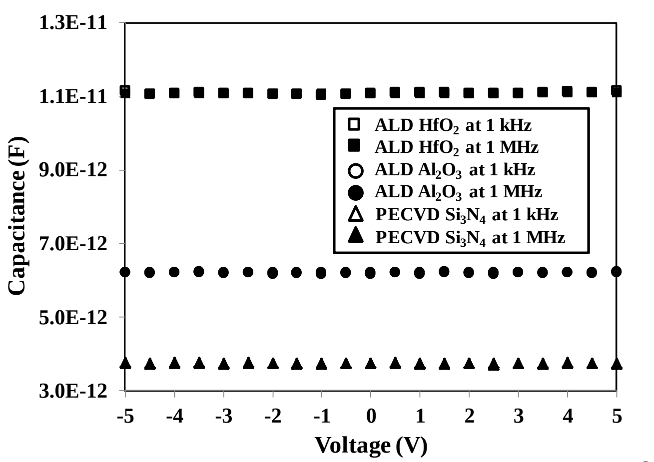

Figure 5. The capacitance of MIM capacitor with an area of 4055 μm^2, as a function of applied voltage and at frequency of 1 kHz and 1 MHz. Some of the data points obtained at 25°C and 150°C overlapped each other.

Figure 6 shows the I-V curves of the MIM capacitor with an area of 4055 μm^2 using these three films, as the applied voltage was increased from 0 V to 100 V, and at the temperatures of 25°C and 150°C. As can be seen, the capacitor with 59 nm PECVD Si_3N_4 resulted in the lowest leakage current density, while that with HfO_2 resulted in the highest leakage current density. Furthermore, as the temperature was increased, the leakage current density increase was higher for the ALD HfO_2 and Al_2O_3 films. There were some non-linear I-V characteristics in certain voltage ranges of these films, possibly indicating that there may be multiple carrier conduction processes occurring, when the voltage bias was applied, including Schottky, Frenkel-Poole, and Fowler-Nordheim tunneling emissions [2,15,17].

Figure 6 also shows the breakdown voltage characteristics of the MIM capacitors with these three different dielectric films. As can be seen, the PECVD Si_3N_4 has the highest breakdown voltage of 73 V, while ALD Al_2O_3 and HfO_2 have a breakdown voltage of 41 V and 34 V, respectively. Figure 7 shows the breakdown voltage of the three films at temperatures of 25°C and 150°C. It can be seen that the breakdown voltage of ALD Al_2O_3 and HfO_2 decreased to 31 V and 26 V, respectively, while that of PECVD Si_3N_4 decreased to 68 V, when the temperature was increased from 25°C and 150°C. These data show that the PECVD Si_3N_4 is more suitable as capacitor dielectric for MIM capacitors in GaAs designs for high power applications, such as driver amplifiers in infrastructure and base station applications, while the ALD Al_2O_3 and HfO_2 may be suitable for capacitors in GaAs RF designs for cellular and wireless amplifier applications.

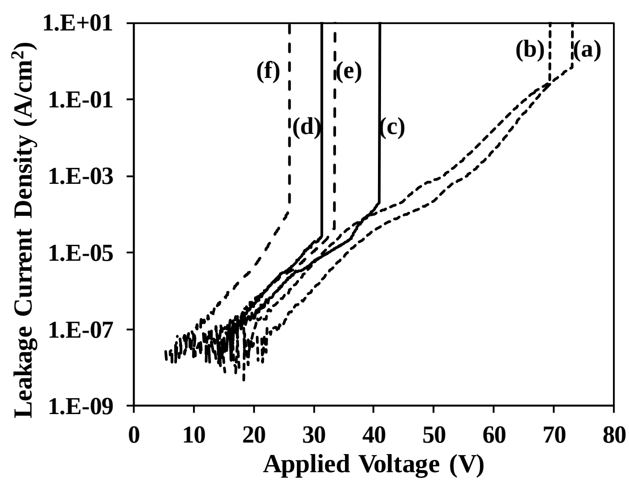

Figure 6. The I-V characteristics of MIM capacitor with capacitor dielectric of 60+/-3 nm (a) PECVD Si_3N_4 at 25°C, (b) PECVD Si_3N_4 at 150°C, (c) ALD Al_2O_3 at 25°C, (d) ALD Al_2O_3 at 150°C, (e) ALD HfO_2 at 25°C, and (f) ALD HfO_2 at 150°C.

As the capacitor area in GaAs designs can vary significantly, it is important to evaluate the effect of the MIM capacitor area on the electrical characteristics. Figure 7 shows the breakdown voltages of MIM capacitor with ALD Al_2O_3, ALD HfO_2, and PECVD Si_3N_4, as a function of MIM capacitor area. No significant difference was observed in the breakdown voltage of these three films, when the capacitor area was increased from 100 μm^2 to 10,000 μm^2.

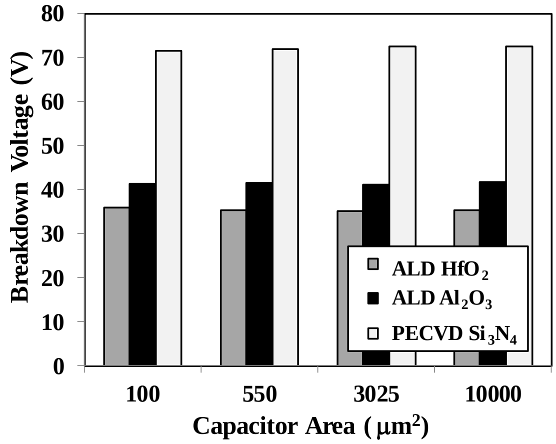

Figure 7. The breakdown voltage of MIM capacitor with capacitor dielectric 60+/-3 nm of ALD HfO_2, ALD Al_2O_3, and PECVD Si_3N_4 as a function of capacitor area.

Figure 8 shows the extracted quality factor of the MIM capacitor at various frequencies, when these three films were used as capacitor dielectric on GaAs HBT wafers. The results show that the quality factor at 1 GHz of the MIM capacitor with ALD HfO_2 and Al_2O_3 was lower than that with PECVD Si_3N_4 by about 50%. Additionally, the quality factor of the ALD HfO_2 degraded at a higher rate than that of ALD Al_2O_3, as the frequency was increased from 1 GHz to 5 GHz. Due to the higher loss in the ALD films as indicated by their lower quality factor than that of the PECVD Si_3N_4 film, MIM capacitors with these ALD HfO_2 and Al_2O_3 films will be more suitable for realizing capacitors in the input- or inter-stage matching network than in the output matching network of a GaAs RF power amplifier designs.

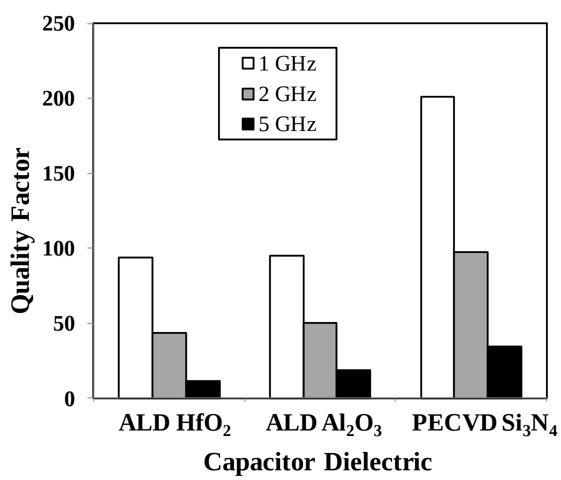

Figure 8. The quality factor of MIM capacitor with ALD HfO_2, ALD Al_2O_3, and PECVD Si_3N_4 as capacitor dielectric, as a function of frequency.

These results show that each of the three films of 60 nm +/- 3 nm ALD HfO_2, ALD Al_2O_3, and PECVD Si_3N_4 have different advantages in terms of electrical characteristics. The ALD HfO_2 and Al_2O_3films in this study have significantly higher capacitance density than PECVD Si_3N_4. However, the PECVD Si_3N_4 has lower leakage current, higher breakdown voltage, and higher quality factor than the ALD films. These data show that the ALD HfO_2 and Al_2O_3 films, in addition to the PECVD Si_3N_4 film, all of which were deposited at $\leq 300^{o}C$, are compatible with, and can be used as MIM capacitor dielectric for GaAs HBT technology. The capacitor dielectric film can be selected based on the GaAs HBT MIM capacitor specific electrical characteristics requirements, application, and operating conditions of the design.

CONCLUSIONS

We have characterized thin films of ALD HfO_2, ALD Al_2O_3 and PECVD Si_3N_4 as MIM capacitor dielectric for GaAs HBT technology. The results show that these three films have different advantages in terms of capacitance, leakage current, breakdown voltage, and quality factor. These films are shown to be compatible with, and are suitable as MIM capacitor dielectric for GaAs HBT technology. The MIM dielectric film can be selected based on the specific electrical requirements, application, and operating conditions of the GaAs RF design.

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REFERENCES

[1] J. Yota, et al., *2003 GaAs MANTECH Technical Digest*, pp. 65-68, 2003.
[2] J. Yota, et al., *J. Vac. Sci. Technol. A*, **31**, 01A134 (2013).
[3] W. Liu, *Handbook of III-V Heterojunction Bipolar Transistors,* New York, John Wiley, 1998.
[4] J. Yota, *ECS Trans,*, **53(1)**, 281 (2013).
[5] R. J. Slater, *2010 CS MANTECH Technical Digest*, pp. 78-79, 2010.
[6] Y. Yang, et al., *2010 CS MANTECH Technical Digest*, pp. 55-58, 2010.
[7] J. Scarpulla, et al., *Proc. 37th Int. Rel. Phys. Symp*., pp. 128-137, 1999.
[8] J. Beall, et al., *2002 GaAs MANTECH Technical Digest*, pp. 145-148, 2002.
[9] M. Brophy, et al., *2003 GaAs MANTECH Technical Digest*, pp. 57-60, 2003.
[10] R. Williams, *Modern GaAs Processing Methods,* Norwood, Artech House, 1990.
[11] S. M. Sze, *VLSI Fabrication Technology*, New York, McGraw-Hill, 1988.
[12] J. Yota, et al., *IEEE Trans. Semicond. Manuf*., **20**, 323 (2007).
[13] J. J. Kim, et al., *IEEE Trans. Electron. Dev*., **60**, 3683 (2013).
[14] T. H. Phung, et al., *J. Electrochem. Soc*., **158**, H1289 (2011).
[15] N. Alimardani, et al., *J. Vac. Sci. Technol. A*, **30**, 01A113 (2012).
[16] H. B. Profijt, et al., *J. Vac. Sci. Technol. A*, **29**, 00801 (2011).
[17] S. M. Sze, *Physics of Semiconductor Devices,* New York, Wiley, 1981.

ACRONYMS

HBT: Heterojunction Bipolar Transistor
MIM: Metal-Insulator-Metal
ALD: Atomic Layer Deposition
PECVD: Plasma-Enhanced Chemical Vapor Deposition