ALD HfO$_2$, Al$_2$O$_3$, and PECVD Si$_3$N$_4$ as MIM Capacitor Dielectric for GaAs HBT Technology

Jiro Yota, Kai Kwok, and Ravi Ramanathan
GaAs Technology, Skyworks Solutions, Inc., 2427 W. Hillcrest Dr., Newbury Park, CA 91320
Email: jiro.yota@skyworksinc.com

The die size in semiconductor wafer manufacturing must be reduced, due to the increasing demand for capacity and increasing complexity and functionality of devices in IC designs. One of the methods to reduce the die size is to increase the capacitance density of the metal-insulator-metal (MIM) capacitor, which is a key passive component in GaAs RF designs. A higher capacitance density capacitor will allow the reduction of the capacitor area, resulting in die size reduction. This 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 also requires high breakdown voltage, low leakage current, and high quality factor. The most widely used MIM capacitor dielectric in GaAs technology is plasma-enhanced chemical vapor deposition (PECVD) silicon nitride (Si$_3$N$_4$). This film is known to have relatively good electrical, physical, and chemical characteristics. It is also compatible with GaAs technology, and can be deposited at temperature of ≤300°C. However, PECVD Si$_3$N$_4$ has only a dielectric constant $\kappa$ of only 6-7, resulting in capacitance density that is relatively low.

Recently, atomic layer deposition (ALD) method has been used to deposit high quality dielectric films at low temperatures. In this study, we have evaluated and characterized ALD hafnium dioxide (HfO$_2$) and aluminum oxide (Al$_2$O$_3$) as MIM capacitor dielectric for GaAs hetero-junction bipolar transistor (HBT) technology, and compared the results to those of PECVD Si$_3$N$_4$. All three films were 60 +/- 3 nm thick. The ALD HfO$_2$ was deposited at 230°C using tetrakisethylmethylamino hafnium, water, and O$_3$, while the ALD Al$_2$O$_3$ was deposited at 300°C using trimethyl aluminum, water, and O$_2$. The PECVD Si$_3$N$_4$ was deposited at 300°C using SiH$_4$, NH$_3$, and N$_2$. Fig. 1 shows the capacitance density obtained when these 3 films were used as MIM capacitor dielectric. As can be seen, the capacitance density of MIM capacitor with ALD HfO$_2$ (2.73 fF/μm$^2$) and Al$_2$O$_3$ (1.55 fF/μm$^2$) is significantly higher than that with PECVD Si$_3$N$_4$ (0.92 fF/μm$^2$). Fig. 2 shows that the dielectric constant of ALD HfO$_2$ and Al$_2$O$_3$ is 18.7 and 10.3, respectively, as compared to that of PECVD Si$_3$N$_4$ which is 6.5. However, the breakdown field of the ALD HfO$_2$ (5.4 MV/cm) and Al$_2$O$_3$ (7.0 MV/cm) is lower than that of PECVD Si$_3$N$_4$ (11.6 MV/cm). Fig. 3 shows the IV characteristics of these 3 films, when the temperature was increased from 25°C to 150°C. The results show that as the temperature was increased, the leakage current density of all films increased. However, the PECVD Si$_3$N$_4$ leakage current density is significantly less than that of both ALD HfO$_2$ and Al$_2$O$_3$. Furthermore, the data also show that the breakdown voltage of ALD HfO$_2$ and Al$_2$O$_3$ is lower than that of PECVD Si$_3$N$_4$, and is reduced significantly more when the temperature was increased from 25°C to 150°C. Fig. 4 shows the quality factor of the MIM capacitor extracted from S-parameter measurement, when these three films were used as capacitor dielectric on GaAs HBT wafers. It can be observed that the quality factor of the MIM capacitor with ALD HfO$_2$ and Al$_2$O$_3$ is lower than that with PECVD Si$_3$N$_4$ by about 50%.

These results show that each of the three films of ALD films of HfO$_2$ and Al$_2$O$_3$, and PECVD Si$_3$N$_4$ have different advantages in terms of electrical characteristics. The ALD films in this study have significantly higher capacitance density than PECVD Si$_3$N$_4$. However, the PECVD Si$_3$N$_4$ has lower leakage current, higher breakdown field, and higher quality factor than the ALD films. These data show that the ALD HfO$_2$ and Al$_2$O$_3$ films, in addition to the PECVD Si$_3$N$_4$ film, can be used as MIM capacitor dielectric for GaAs HBT technology, and can be selected based on the GaAs HBT MIM capacitor specific electrical characteristics requirements, application, and operating conditions.
Fig 1. Capacitance density of MIM capacitor with 60+/-3 nm of ALD HfO₂, ALD Al₂O₃, and PECVD Si₃N₄ as capacitor dielectric on GaAs.

Fig 2. Dielectric constant and breakdown field of ALD HfO₂, ALD Al₂O₃, and PECVD Si₃N₄.

Fig 3. The I-V characteristics of GaAs MIM capacitor with capacitor dielectric 60+/-3 nm: (a) PECVD Si₃N₄ at 25°C, (b) PECVD Si₃N₄ at 150°C, (c) ALD Al₂O₃ at 25°C, (d) ALD Al₂O₃ at 150°C, (e) ALD HfO₂ at 25°C, and (f) ALD HfO₂ at 150°C.

Fig 4. Quality factor of MIM capacitor with 60+/-3 nm of ALD HfO₂, ALD Al₂O₃, and PECVD Si₃N₄ as capacitor dielectric on GaAs.