On the Development of High Density Nitrides for MMICs

Y. C. Chou, R. Lai, G. P. Li*, H. Guan*, R. Grundbacher, P. Nam, H. K. Kim**, Y. Ra**, M. Barsky, M. Biedenbender, and A. Oki

Northrop Grumman Space Technology, Redondo Beach, CA 90278
Tel: (310) 812-3550, Fax: (310) 813-0418, Email: yeong-chang.chou@trw.com
*** Department of Electrical Engineering and Computer Science, UC, Irvine, CA 92697**
**** Bethel Material Research, Placentia, CA 92870**

Keywords: High Density, Inductively-Coupled Plasma, High Electron Mobility Transistor, Monolithic Microwave Integrated Circuit

Abstract

We have developed a NH_3 free high-density nitride process (high-density inductively-coupled plasma, HD-IP-CVD) for GaAs HEMT MMIC manufacturing, including its use in devices passivation and as dielectrics for MIMCAPs. We have explored the process optimization in order to minimize the adverse effects of high-density nitrides on the performance of devices and MMICs. This study suggests that the MMIC performance be optimized at ICP source RF power of approximately 500 watts. On the other hand, the ramp-up breakdown voltage of MIMCAPs of high-density nitrides shows an improvement of approximately 50-70% over that of standard PECVD. The result indicates that a better nitride quality of MIMCAPs can be achieved with HD-ICP-CVD process.

INTRODUCTION

Nitride deposition with $SiH_4/NH_3/N_2$ has been widely used in compound semiconductor industry. Its applications include device passivation of metal-semiconductor field-effect transistors (MESFETs) [1], high-electron-mobility transistors (HEMTs) [2-3], and heterojunction bipolar transistors (HBTs) [4-6], dielectric layers for metal-insulator-metal capacitors (MIMCAPs) [7], and glassivation to prevent chips from mechanical damage during the large-volume assembly. In the past, the properties of nitride film were investigated to reduce the adverse effects in the applications noted above. The investigation was primarily focused on optimizing nitride deposition conditions to alleviate the device degradation induced by the nitride process [8-12], undesirable high leakage current in MIMCAPs [7], and nitride crack induced hermeticity problems [13].

Due to the use of $SiH_4/NH_3/N_2$ gaseous species in the standard plasma-enhanced chemical vapor deposition (PECVD), nitrides were detected to have high hydrogen concentration. The hydrogen content in the nitrides might be released through the subsequent processes, thus degrading the device performance. PECVD nitrides are also known not to possess enough density to prevent the penetration of hydrogen from the housing of integrated microwave assemblies (IMAs) for space applications and to protect the MMIC chips from being affected by high humidity atmosphere for commercial applications. In order to properly address these requirements, it is essential to develop a new nitride deposition technique capable of producing nitrides with low hydrogen content and high density. Thus, MMICs will have better reliability in the hydrogen exposed environment and better hermeticity in the high humidity environment.

In this paper, we explored the development of high-density nitride deposition using inductively coupled plasma chemical vapor deposition (HD-ICP-CVD) to passivate GaAs PHEMT devices and MMICs. The deposition conditions of high-density nitrides were optimized to minimize the degradation of devices and MMICs induced by the ICP plasma exposure. Furthermore, use of high-density nitrides as the dielectric of MIMCAPs was investigated. The ramp-up breakdown voltage of MIMCAPs with high-density nitrides shows an improvement of approximately 50-70% over that of standard PECVD MIMCAPs. The result suggests that a better nitride quality of MIMCAPs can be obtained with HD-ICP-CVD process.

EXPERIMENTAL

Bethel Material Research developed an HD-ICP-CVD system (HiDep2000) for this study. The nitrides were deposited with gaseous species of SiH_4 and N_2 (NH_3 free process). Due to the HD-ICP-CVD deposition process, the nitride films were demonstrated to have lower hydrogen content and higher density than those of PECVD nitrides [14]. The system is featured with an adjustable plasma RF source from 250 watts to 2000 watts and a controllable substrate temperature from 50°C to 200°C. More details of HD-ICP-CVD novel nitride deposition technique were described in Reference 15. In our investigation, GaAs PHEMTs with a gate length of 0.15 μm were passivated by the first high-density nitride with a thickness of 250Å, followed by the second high-density nitride with a thickness of 500Å. The device characteristics were measured before and after high-density nitride passivation to evaluate the impact of nitride deposition conditions on device performance. The process used here is Northrop Grumman Space Technology 0.15 µm GaAs PHEMTs with high reliability performance [16].

RESULTS ON DEVICES AND MMICS

To investigate the effects of ICP source RF power on device performance, GaAs PHEMTs before and after HD-ICP-CVD nitride passivation were fully characterized. Figure 1 shows the effects of ICP source RF powers from 500 watts to 2000 watts on device performance (e.g., peak transconductacne (G_{mp}) and maximum channel current (I_{max}). It has been found that device performance strongly depends upon the ICP source RF power. Nevertheless, the amount of device degradation has been minimized with the ICP source RF power less than 500 watts. Higher ICP source RF power could introduce damage to the devices, thus leading to the degradation of transconductance (G_m), and drain current (I_{ds}). The decreases of transconductance and drain current are typically observed in the degraded devices, while the V_{gp} (V_g at peak G_m) and pinchoff voltage (V_{po}) are slightly affected [17]. Furthermore, we have found that the I_{ds} degradation rate at more positive V_g is higher than that at more negative V_g. This information signifies that the device degradation induced by HD-ICP-CVD process is mainly due to an increase of access resistance on source and drain regions [17]. A separate measurement of source resistance (R_s) and drain resistance (R_d) confirms indeed that device degradation is due to the increase of R_s and R_d. Figure 2 shows the R_s and R_d correlation with G_{mp} on the devices passivated by HD-ICP-CVD and PECVD. It has been found that G_{mp} degradation for samples deposited at 2000 watts is accompanied with an increase of R_s and R_d.

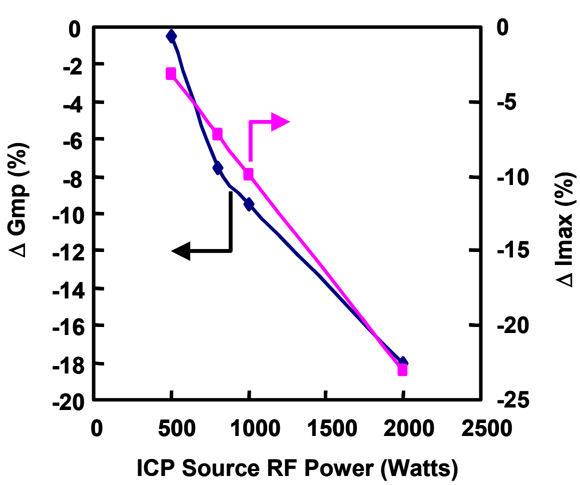

Figure 1. The dependence of ΔG_{mp} and ΔI_{max} on ICP source RF power. (PECVD shows negligible changes of ΔG_{mp} and ΔI_{max} after passivation).

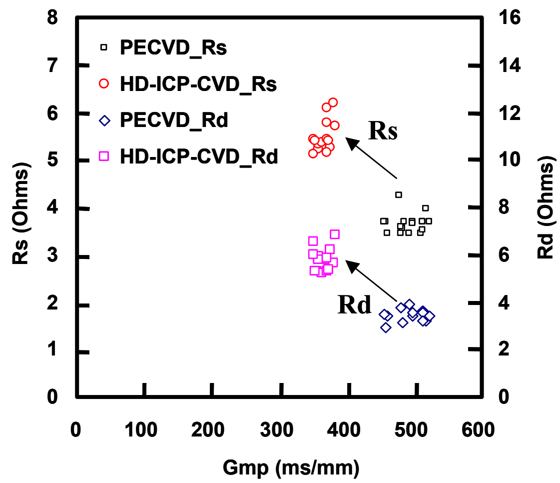

Figure 2. Correlation of R_s and R_d versus G_{mp} on the devices of HD-ICP-CVD nitride deposited with an ICP source RF power of 2000 watts and PECVD.

During the HD-ICP-CVD nitride deposition, the source and drain recess regions were exposed to the high-density plasma atmosphere. The surface properties of the recessed AlGaAs regions could be damaged owing to the non-optimized deposition conditions. The damaged AlGaAs regions will further deplete the channel carrier, thus causing the increase of the R_s and R_d. In the case of ICP source RF power of 2000 watts, R_s and R_d could be increased up to 70%. This effect has been minimized with ICP source RF power less than 500 watts. The device DC characteristics degradation also leads to worsen RF characteristics (e.g., cut-off frequency, and maximum stable gain). Figure 3 shows the effects of ICP source RF power on F_t, illustrating reduction of F_t from 89-90 GHz at ICP power of 500 watt to 70-75 GHz at 2000 watts.

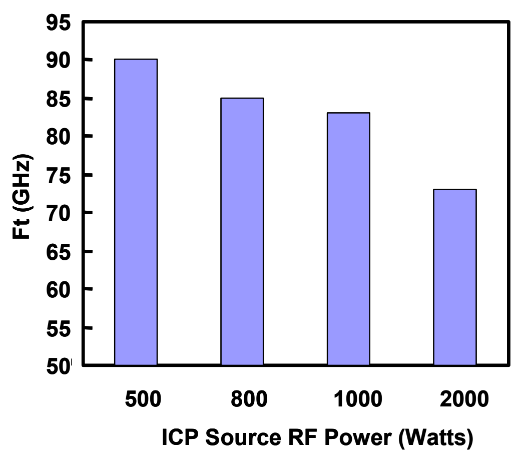

Figure 3. The dependence of F_t on ICP source RF power (PECVD exhibits F_t of 85-90 GHz).

To investigate the effect of HD-ICP-CVD nitride deposition conditions on MMIC performance, Ka-band balanced amplifiers were fabricated for this study. The dependence of noise figure at 35 GHz on ICP source RF power is shown in Figure 4. It is noticed that as ICP source RF power is increased, noise figure of the amplifier increases. The increase of noise figure was attributed to an inferior device performance in those passivated with high ICP source power. However, the associated gain performance measured at 35 GHz is shown to be insensitive to the ICP source power in the range of 500 watts to 1000 watts (shown in Figure 5). This could be attributed to the amplifiers used in this study being less sensitive to the device parameter variations.

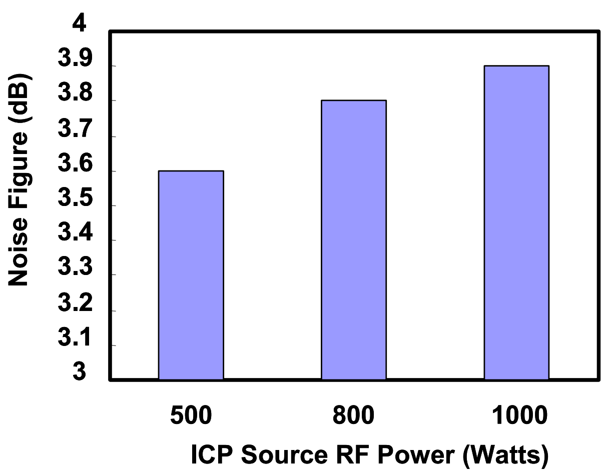

Figure 4. The dependence of MMIC noise figures on ICP source RF power (MMICs processed with PECVD nitrides exhibit the noise figure performance of 3.5-3.6 dB at 35 GHz).

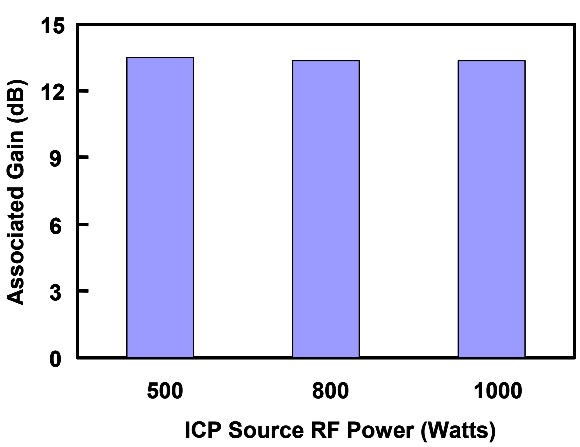

Figure 5. The dependence of MMIC associated gain on ICP source RF power (MMICs processed with PECVD nitrides exhibit the associated gain performance of 13.5-14 dB at 35 GHz).

The best MMIC performance was achieved at ICP source RF power less than 500 watts. However, the quality of nitride films, i.e. hydrogen content and nitride density are deteriorated at much lower ICP source RF power [18]. Therefore, there is a tradeoff between MMIC performance and nitride quality, depending on the nitride deposition conditions of ICP source RF power. From our investigation, the compromise of MMIC performance and nitride quality was achieved at ICP source RF power of approximately 500 watts.

RESULTS ON MIMCAPS

The HD-ICP-CVD process was also investigated for its use as dielectric of MIMCAPs. The first nitride was deposited at ICP source RF power of 500 watts and substrate temperature of 170^{o}C. The second nitride was deposited at ICP source RF power of 500 watts and lower substrate temperature of 85^{o}C due to the liftoff 2nd nitride process employed in our technology. The ramp-up breakdown measurement of MIMCAPs was used to evaluate the quality of HD-ICP-CVD MIMCAPs. The results were compared to those of MIMCAPs deposited with PECVD nitrides. As shown in Figure 6, it is evident that the ramp-up breakdown voltage of HD-ICP-CVD nitride is improved by approximately 50-70% over that of PECVD MIMCAPs. This result suggests that high-density nitride could be an alternative candidate for the MIMCAPs in MMICs. Especially, it will be able to meet the requirement of having either high ramp-up breakdown voltage, or moderate breakdown voltage but with a higher unit capacitance (i.e. a thinner nitride film).

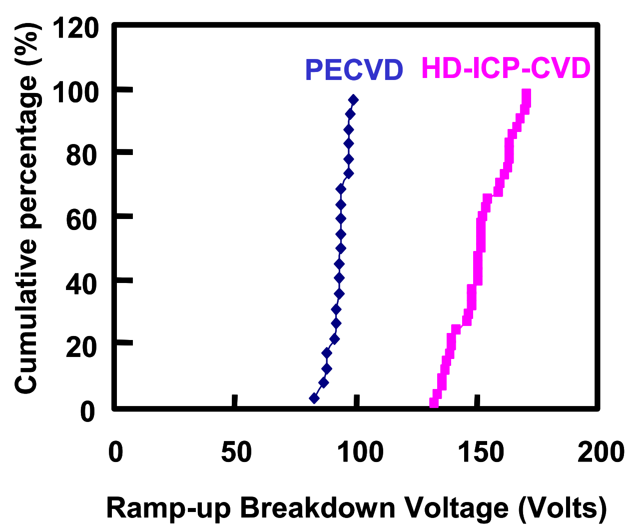

Figure 6. Ramp-up breakdown voltage of MIMCAPs: HD-ICP-CVD versus PECVD.

CONCLUSIONS

We have developed high-density nitrides with gaseous species of SiH_4 and N_2 process (NH_3 free) for GaAs PHEMT MMIC manufacturing, including its use in devices passivation and as dielectrics for MIMCAPs. We have observed a tradeoff of MMIC performance and nitride quality with respect to hydrogen content and nitride density. While higher quality nitride could be obtained with higher ICP source RF power, device performance is degraded due to damage induced by the high-density plasma in the exposed recess regions. From this study, the compromise between MMIC performance and nitride quality could be obtained at an ICP source RF power of approximately 500 watts. Furthermore, the ramp-up breakdown voltage of MIMCAPs with high-density nitrides shows an improvement of approximately 50-70% over that of standard PECVD MIMCAPs. The result indicates that a better nitride quality of MIMCAPs can be achieved with HD-ICP-CVD process.

ACKNOWLEDGEMENTS

The authors would like to thank the people that helped the development of HD-ICP-CVD nitride processes in Bethel Material Research. Additionally, support from the areas of wafer processing and RF MMIC testing at Northrop Grumman Space Technology was also appreciated.

REFERENCES

[1] J. G. Tenedorio and P. A. Terizian, "*Effects of Si_3N_4, SiO, and polyimide surface passivation on GaAs MESFET amplifier RF stability*," in IEEE Electron Devices Lett., vol. 5, pp. 199-202 (1984).

[2] E. Y. Chang, G. T. Cibuzar, and K. P. Pande, "*Passivation of GaAs FET's with PECVD Silicon Nitride Films of Different Stress Sates*", in IEEE Electron Device, vol. 35, pp. 1412-1418 (1988).

[3] J. J. Brown, A. E. Echmitz, M. Hu, J. A. Pusl, J. B. Shealy, D. P. Docter, M. A. Thompson and L. D. Nguyen, "*GaAs PHEMT Device passivation Technology for High Efficiency Power Amplifier Applications*", 1996 GaAs MANTECH Technical Digest, pp. 187-190, 1996.

[4] R. T. Yoshioka, L. E. M. de Barros, J. A. Diniz and J. W. Swart, "*Improving Performance of Microwave AlGaAs/GaAs HBTs Using Novel SiN_x Passivation Process*", in Proceedings of the IEEE MTT Symposium, pp. 108-111, 1999.

[5] C. J. Snadroff et al., "*Dramatic enhancement the gain of a GaAs/AlGaAs heterostructure bipolar transistors by surface chemical passivation*", in Appl. Phys. Lett., vol. 51, pp. 33-35 (1987).

[6] A. Kapila, "*Passivation of GaAs surfaces and AlGaAs/GaAs heterojunction bipolar transistors using sulfide solution and SiN_x ovelayer*", in *J. Vac. Sci. Technol.,* B-13 pp. 10-15 (1995).

[7] J. Scarpulla, D. Eng, S. Olson and C. S. Wu "*A TDDB Model of Si_3N_4-biased Capacitors in GaAs MMICs*", in Proceedings of International Reliability Physics Symposium, pp. 128-137, 1999.

[8] H. Wang, G. I. Ng, H. Yang and K. Radhakrishnan, "*Ammonia (NH_3) Plasma Surface Passivation of InP/InGaAs Heterojunction Bipolar Transistors*," in Proceedings of International Conference of InP and Related Material, pp. 421-424, 2001.

[9] H. Moriguchi, S. Hoshi, T. Ohshima, T. Izumi and T. Kimura, "*Isolation Degradation of InAlAs/InGaAs/InP HEMTs Due to Bias Stress Depending on Passivation Films Formed by PCVD*," in Proceedings of International Conference of InP and Related Material, pp. 417-420, 2001.

[10] H. Wang, G. I. Ng, H. Yang and K. Radhakrishnan, "*Understanding the Degradation of InP/InGaAs Heterojunction Bipolar Transistors Induced by Silicon Nitride Passivation*," in Proceedings of International Conference of InP and Related Material, pp. 252-255, 2001.

[11] J. W. Lee, C. R. Abernathy, S. J. Pearton, F. Ren, C. Constantine, C. Barratt and R. J. Shul, "*Comparison of Dry Etch Damage in GaAs/AlGaAs Hereojunction Bipolar Transistors Exposed to ECR and ICP Ar Plasmas*," in Solid State Electronics, vol. 42, pp. 733-742 (1998).

[12] F. Ren, R. F. Kopf, J. M. Kuo, J. R. Lothian, J. W. Lee, S. J. Pearton, and R. J. Shul, C. R. Abernathy, C. Constantine and D. Johnson "*Effect of High Density H_2 Plasmas on InGaP/GaAs and AlGaAs/GaAs HEMTs*," in Solid State Electronics, vol. 42, pp. 749-753 (1998).

[13] W. J. Roesch, S. Peterson, A. Poe, S. Brockett, S. Mahon and J. Bruckner, "*Assessing Circuit Hermeticity by Electrolysis*," in GaAs MANTECH Technical Digest, pp. 121-124, 2000.

[14] Y.C. Chou, R. Lai, G. P. Li, P. Nam, H. K. Kim, Y. Ra, R. Grundbacher, E. Ahlers, M. Barsky, M. Biedenbender and O. Oki, "*Novel Nitride Passivation on 0.15 μm Pseudomorphic GaAs HEMTs Using High-Density Inductively Coupled Plasma CVD (HD-ICP-CVD)*," in Proceedings of International GaAs Mantech Conference, pp. 91-94, 2002.

[15] J. Hua, "The Development of Novel Low-Temperature ICPCVD Nitride Process," Master Thesis in UC, Irvine, 2001.

[16] D. Leung, Y.C. Chou, C.S. Wu, R. Kono, R. Lai, M. Hoppe and D.C. Streit, "*High Reliability Non-Hermetic 0.15 μm GaAs Pseudomorphic HEMT MMIC Amplifiers*", in Proceedings of the RF Integrated Circuits Symposium, pp. 261-267, 1999.

[17] Y.C. Chou, P. Nam, G. P. Li, R. Lai, H. K. Kim, R. Grundbacher, E. Ahlers, Y. Ra, Q. Xu, M. Biedenbender and O. Oki, "*Innovative Nitride Passivation on Pseudomorphic GaAs HEMTs and its Impact on Devices Performance*," in Proceedings of International Reliability Physics Symposium, pp. 235-240, 2002.

[18] Private information in Bethel Material Research.

ACRONYMS

HD-ICP-CVD: High Density Inductively Coupled Plasma Chemical Vapor Deposition
PECVD: Plasma-Enhanced Chemical Vapor Deposition
MIMCAP: Metal-Insulator-Metal Capacitor
MESFET: Metal-Semiconductor Field Effect Transistor
HEMT: High Electron Mobility Transistor
HBT: Heterojunction Bipolar Transistor
MMIC: Monolithic Microwave Integrated Circuit