Novel Nitride Passivation on 0.15 μm Pseudomorphic GaAs HEMTs Using High-Density Inductively Coupled Plasma CVD (HD-ICP-CVD)

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Abstract

A novel nitride passivation on 0.15 μm pseudomorphic GaAs HEMTs using high-density inductively coupled plasma CVD (HD-ICP-CVD) is reported. The nitride films deposited by HD-ICP-CVD have a lower BOE wet etch rate (high density) and lower hydrogen concentration than those nitride films deposited by PECVD. A successful demonstration of DC/RF performance and its thermal stability in HD-ICP-CVD passivated PHEMTs and MMIC performance comparable to that of MMICs passivated by PECVD promises the applications of HD-ICP-CVD nitride deposition for the next-generation passivation technique in compound semiconductor industry.

INTRODUCTION

Silicon nitrides are widely used in many electronic devices of compound semiconductors (primarily in GaAs and InP) manufacturing for the wireless applications, including devices passivation of metal-semiconductor field-effect transistors (MESFETs) [1], high electron mobility transistors (HEMTs) [2-3], hetero-junction bipolar transistors (HBTs) [4-6], masking layers, dielectric layers for metal-insulator-metal (MIM) capacitors [7], and encapsulation to protect against the environmental induced degradation or mechanical scratches. For the nitride passivation of MESFETs and HEMTs, the recess regions of gate-source and gate-drain are fully passivated with silicon nitride films to inhibit the atmospheric induced degradation [8]. Firstly, the degradation of devices characteristics has been observed in GaAs MESFETs and GaAs pseudomorphic HEMTs (PHEMTs) [9-11] due to the conversion of gaseous hydrogen (released from the housing of integrated microwave assemblies (IMAs) into the atomic hydrogen. Subsequently, atomic hydrogen atoms could diffuse into the channel regions to neutralize the silicon donors or result in the formation of TiH_x in Ti/Pt/Au gate metal systems [12]. This effect could induce the stress in the gate resulting in the piezo-electric effect, thus causing the devices degradation [13]. Secondly, nitride films have been utilized as the dielectric layers for the metal-insulator-metal capacitors (MIMCAPs) fabrication. The high leakage current of MIMCAPs has been observed on the MIMCAPs due to the poor quality of silicon nitride films [7]. The high leakage current of MIMCAPs leads to the non-function of MMICs due to the additional leaky path along the bypassing MIMCAPs, thereby reducing the RF circuit yield. Thirdly, the improper circuit hermeticity due to the nitride crack provides an additional moisture path into the circuitry, thus causing the unexpected failure [14]. For HBT's applications, the surface recombination occurring on the emitter mesa wall and extrinsic base region results in the increase of surface recombination current, thereby reducing the injection efficiency and device current gain. Recently, silicon nitride passivation on HBTs of AlGaAs/GaAs or InP/InGaAs has been widely explored in order to optimize the processes for reducing the surface recombination and improving the current gains of HBTs [15-19]. It has been found that the surface recombination and current gain could be improved with either different deposition techniques or special plasma treatments. Because of the strong dependence of device performance upon the nitride deposition processes, it is essential to have a better passivation technique for the future compound semiconductor manufacturing.

Currently, in compound semiconductor industry, silicon nitrides were deposited by plasma-enhanced chemical vapor deposition (PECVD) for the standard passivation technique. In PECVD, silicon nitride films are deposited with $SiH_4/NH_3/N_2$ at lower deposition temperatures ranging from 100°C to 250°C. PECVD's nitride films have higher hydrogen content due to the use of gaseous species of $SiH_4/NH_3/N_2$. The hydrogen content in the nitride film might be released through the processes, therefore deteriorating the devices performance. Also, the stress and the density of PECVD's nitride films still need to be further optimized in order to improve devices performance, particularly the breakdown voltages reduction after passivation and its hermeticity. As a result, there is strong need to develop a new passivation technique in order to reduce the hydrogen in

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the nitride films and improve the hermeticity for commercial applications in the non-hermetic environment.

In this paper, HD-ICP-CVD passivation technique with SiH_4/N_2 was developed to offer the silicon nitride films with high-density and low hydrogen content. The investigation shows the promising results of using HD-ICP-CVD for the nitride passivation in compound semiconductor technologies.

EXPERIMENTAL

Bethel Material Research developed an HD-ICP-CVD system (HiDep2000) for this investigation. In an HD-ICP-CVD system as shown in Figure 1, gaseous species of SiH_4 and N_2 (NH_3 free process) were developed to offer the nitride films with low hydrogen content. In our investigation, the ICP source RF power was optimized at 500 watts having the minimized induced degradation after the nitride passivation [20], while all the other process parameters were fixed (pressure: 20 mTorr, SiH_4/N_2 flow: 5.5/5 sccm, substrate temperature: 170°C). No RF bias power was applied in our experiment in order to minimize the possible ion bombardment during the nitride deposition. 3 amps of the magnet field were applied onto the magnet at the sidewall of the chamber to further enhance the plasma density. More details of HD-ICP-CVD deposition technique were described elsewhere [21]. After the gate process, 0.15µm GaAs PHEMTs were passivated by the 1st nitride with a thickness of 250 Å, followed by the 2nd nitride with a thickness of 500 Å at a later step. The fabrication of 0.15µm GaAs PHEMTs is TRW's baseline processes reported elsewhere [8].

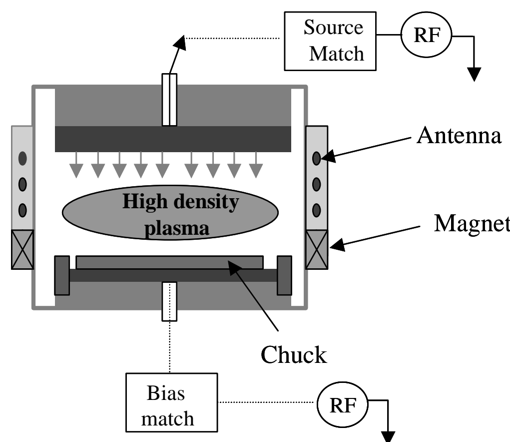

Figure 1. Configuration of an HD-ICP-CVD system using SiH_4/N_2 for silicon nitride passivation on 0.15 µm GaAs PHEMTs.

Silicon nitride wet etch rate as a function of deposition parameters was constantly monitored to examine the film density. As shown in Figure 2, the BOE wet etch rate of nitrides deposited by HD-ICP-CVD strongly depends upon the ICP source RF power. At a deposition temperature of 170°C with ICP source RF power at 500 watts, the wet etch rate of HD-ICP-CVD nitrides is approximately 220-240 Å/min, which is lower than that of typical PECVD's nitrides (≈ 600−1000Å/min). This confirms that the nitride films with higher density than that of PECVD nitrides have been achieved by an HD-ICP-CVD passivation technique. Atomic force microscope (AFM) measurement shows that the nitride deposited by HD-ICP-CVD has a surface roughness of less than 15 Å. Table1 summarizes the process conditions and film characteristics of nitrides deposited by HD-ICP-CVD and PECVD.

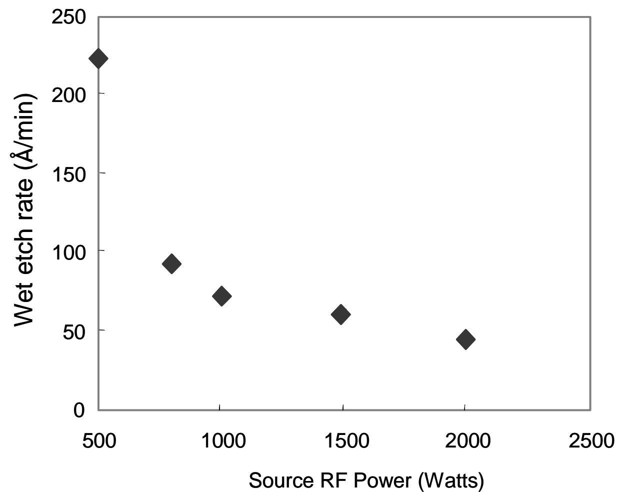

Figure 2. Wet etch rate of HD-ICP-CVD's nitrides as a function of ICP source power at a deposition temperature of 170°C.

TABLE I
PROCESS PARAMETERS & FILM CHARACTERISTICS OF PECVD VERSUS HD-ICP-CVD

Parameters	PECVD	HD-ICP-CVD
Deposition Temperature (°C)	250	170
Deposition Rate (Å/min)	≈100	≈500
Gas Chemistry	$SiH_4/NH_3/N_2$	SiH_4/N_2
Deposition Pressure (mTorr)	900	20
Source RF Power (Watts)	20	> 250
Film Stress	Tensile	Compressive
Wet Etch Rate (Å/min)	600-1000	50-240
Hydrogen content (atomic %)	20-25	< 15

RESULTS AND DISCUSSIONS

Device characteristics of GaAs PHEMTs before and after HD-ICP-CVD nitride passivation were fully characterized to investigate the effects of ICP source RF power on device performance. It has been found that device performance strongly depends upon the ICP source RF power [20]. Higher ICP source RF power could introduce the damages to

the devices, thus leading to the degradation of transconductance (G_m), drain current (I_{ds}), and cut-off frequency (F_t) [20]. The possible process-induced damage mechanism is still under investigation. Nevertheless, the amount of degradation has been minimized with the ICP source RF power less than 500 watts.

Figure 3 shows the representative characteristics of Gm and Ids versus Vgs on 0.15 µm GaAs PHEMTs before and after HD-ICP-CVD nitride passivation (deposited at T_{chuck}=170°C; ICP source RF power= 500 watts). The degradation after nitride passivation is very minute, indicating that the process-induced damage on devices at 500 watts of ICP source RF power is minimal. While a drop of 1.5-2 volts of reverse breakdown on 0.15 µm GaAs PHEMTs after nitride passivation was commonly detected on PECVD processes, however, the changes of breakdown voltage before/after HD-ICP-CVD passivation at 500 watts are negligible, suggesting that surface properties of the materials are not affected by high-density plasma process.

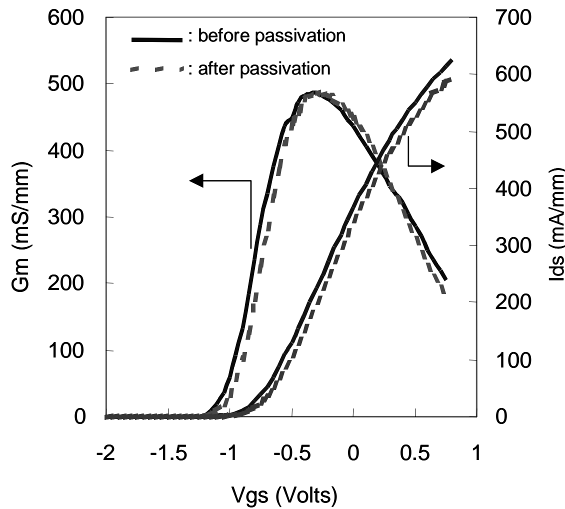

Figure 3. Characteristics of Gm and Ids versus Vgs of 0.15 µm GaAs PHEMTs before/after HD-ICP-CVD nitride passivation.

After completing the front-side processes, devices were subjected to stabaking at 240°C for thermal stability examination. As shown in Figure 4, the initial recoveries of Gmp (peak transconductance) and Imax (maximum Ids at Vg=0.8 V) after stabilization baking for 48 hours were observed. The further prolonged stabake does not change device characteristics. The insert of Figure 4 depicts the recovery of Gm/Ids profiles versus Vgs after stabake at 240°C. The initial recovery of Gm and Ids after stabake was attributed to the annealing effect on the recessed AlGaAs regions. The properties of recessed AlGaAs regions might possibly be modified during the HD-ICP-CVD nitride deposition.

Figure 5 shows the uniform RF characteristics of 9 sites per wafer. The cut-off frequency (F_t) is approximately 85-90 GHz, which is comparable to that of devices passivated by PECVD. This result shows that the uniform RF characteristics on 0.15 µm GaAs PHEMTs have been achieved by an HD-ICP-CVD passivation technique

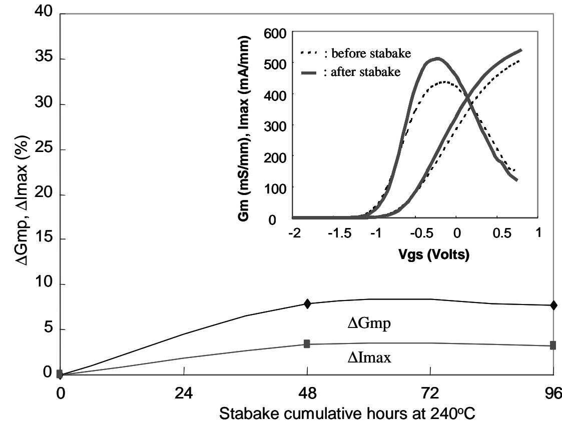

Figure 4. Thermal stability examination of HD-ICP-CVD passivated GaAs PHEMTs (Insert: recovery of characteristics of Gm and Ids versus Vgs after stabake at 240°C for 48 hours).

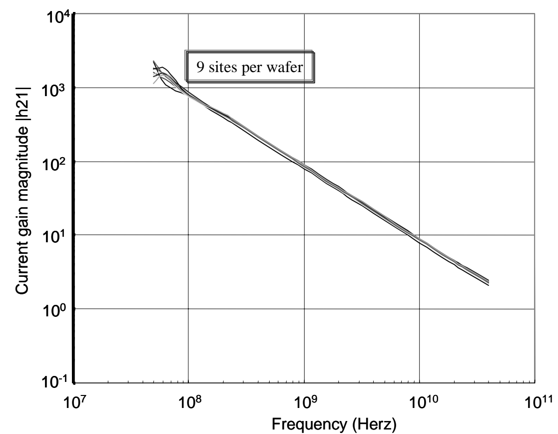

Figure 5. RF characteristics of 0.15 µm GaAs PHEMTs passivated by HD-ICP-CVD nitrides, showing the uniform F_t distribution with a value of approximately 85-90 GHz at Vds=2V.

Figure 6 shows a micrograph of a Ka-band balanced amplifiers passivated by HD-ICP-CVD nitrides. The MMIC exhibits the gain and noise figure of 14 dB and 3.6 dB at 34 GHz as shown in Figure 7, which is comparable to that of MMICs passivated by PECVD. The demonstration of GaAs PHEMT MMICs fabricated with an HD-ICP-CVD passivation technique further warrants the potential insertion of this technique for the future compound semiconductor manufacturing.

CONCLUSIONS

Nitride passivation on 0.15 µm pseudomorphic GaAs HEMTs using high-density inductively coupled plasma

CVD (HD-ICP-CVD) with SiH_4/N_2 (NH_3 free) was investigated. The nitride films deposited by HD-ICP-CVD have a lower BOE wet etch rate (high density) and lower hydrogen concentration than those nitride films deposited by PECVD. The successful demonstration of DC/RF performance and its thermal stability in HD-ICP-CVD passivated PHEMTs and MMIC performance comparable to that of MMICs passivated by PECVD promises the applications of HD-ICP-CVD nitride deposition for the next-generation nitride passivation in compound semiconductor industry.

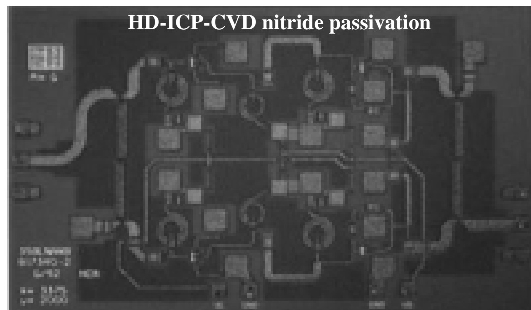

Figure 6. Micrograph of a Ka-band MMIC passivated by HD-ICP-CVD nitrides.

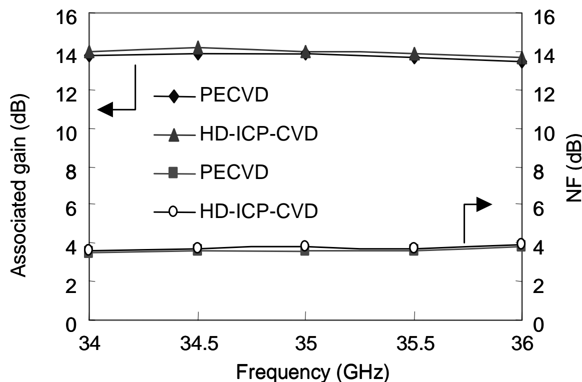

Figure 7. RF performance of a 0.15 µm GaAs PHEMT MMIC passivated by HD-ICP-CVD nitrides, showing the comparable results to MMICs passivated by PECVD.

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