Innovative Low damage Silicon Nitride Passivation of 100nm In0.45AlAs/In0.4GaAs Metamorphic HEMTs with Remote ICPCVD

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In this paper, a novel low-damage silicon nitride passivation for 100 nm In\textsubscript{0.45}AlAs/In\textsubscript{0.4}GaAs MHEMTs has been developed using remote ICPCVD. The silicon nitride deposited by ICPCVD showed higher quality, higher density, and lower hydrogen concentration than those of silicon nitride deposited by PECVD. In particular, we successfully minimized the plasma damage by separating the silicon nitride deposition region remotely from ICP generation region, typically with distance of 34 cm. The silicon nitride passivation with remote ICPCVD has been successfully demonstrated on GaAs MHEMTs with minimized damage. The passivated devices showed considerable improvement in DC characteristics and also exhibited excellent RF characteristics ($f_T$ of 200 GHz). The devices with remote ICPCVD passivation of 50 nm silicon nitride exhibited 22 % improvement (535 mS/mm to 654 mS/mm) of a maximum extrinsic transconductance and 20 % improvement (551 mA/mm to 662 mA/mm) of a maximum saturation drain current compared to those of unpassivated ones, respectively. The results achieved in this work demonstrate that remote ICPCVD is a suitable candidate for the next-generation MHEMT passivation technique.

Introduction

For low noise and high power applications in the millimeter wave range, InAlAs/InGaAs metamorphic high-electron-mobility transistor (MHEMT) on a GaAs substrate is a good alternative to GaAs pseudomorphic HEMT (PHEMT) or InP HEMT. The breakdown characteristics of InP HEMT are poor due to the high indium mole fraction of InGaAs channel. On the contrary, GaAs PHEMT has the high breakdown characteristics, but its millimeter-wave performance is limited by low mobility and saturation velocity of electrons in the channel. These limitations can be overcome by using InAlAs/InGaAs MHEMT on a GaAs substrate [1]. In the MHEMT, InAlAs/InGaAs HEMT structure with high indium mole fraction is grown on a GaAs substrate with a strain relaxed, compositionally graded metamorphic buffer layer, exhibiting substantial cost reduction and manufacturability improvement over the device grown on an InP substrate. The buffer layer provides the ability to tailor the lattice constant to variable indium content of the channel, and therefore allows the device designer an additional
degree of freedom to optimize the transistor structure for high frequency gain, power, linearity, and low noise [2]-[4]. For 77 GHz microwave monolithic integrated circuit (MMIC) applications, the epitaxial layer with indium contents of the channel and the barrier in the range of 30–40 % can lead to improved millimeter wave noise and power characteristics [1]. However, a high aluminum mole fraction in the barrier layer may result in the instability of the device due to surface traps in the gate-recessed regions, which can result in the degradation of MHEMT. Therefore, for the high performance and reliability of the MHEMT, the device must be passivated with a dielectric layer such as a silicon nitride.

Traditionally, silicon nitride deposited by plasma-enhanced chemical vapor deposition (PECVD) has been widely used to passivate the gate-source and the gate-drain recessed regions of metal semiconductor field effect transistors (MESFETs) or HEMTs. Recently, high density inductively coupled plasma-enhanced chemical vapor deposition (ICPCVD) has gained popularity in dielectric film deposition. However, in the devices passivated with conventional ICPCVD silicon nitride, degradations in both the maximum extrinsic transconductance ($g_{m,\text{max}}$) and maximum saturation drain current ($I_{D\text{S,\text{max}}}$) were observed probably due to the damage induced by high density plasma in the exposed gate-recessed regions [5]-[7].

In this paper, a novel low-damage silicon nitride passivation process for 100 nm In$_{0.45}$AlAs/In$_{0.4}$GaAs MHEMTs using remote ICPCVD has been developed. The silicon nitride deposited by remote ICPCVD showed higher quality, higher density, and lower hydrogen concentration than those of silicon nitride deposited by PECVD. In particular, we successfully minimized the plasma damage by separating the silicon nitride deposition region remotely from ICP generation region, typically with distance of 34 cm. The passivated devices with 50 nm of silicon nitride using remote ICPCVD exhibited 22 % improvement (535 mS/mm to 654 mS/mm) in $g_{m,\text{max}}$ and 20 % improvement (551 mA/mm to 662 mA/mm) in $I_{D\text{S,\text{max}}}$ compared to those of unpassivated ones, respectively. Moreover, the fabricated devices with 90 nm dual silicon nitride passivation showed excellent RF characteristics such as a cutoff frequency ($f_T$) of 200 GHz and a maximum oscillation frequency ($f_{\text{max}}$) of 280 GHz.

**Experimental**

**Remote ICPCVD System**

To minimize the possible damage induced by high density plasma, we have modified the ICPCVD system (HiDep$^{\text{TM}}$) developed by BMR Technology Corporation. First, we separated the silicon nitride deposition region remotely from ICP generation region by using movable chuck, typically with the distance of 34 cm. Figure 1 shows the schematic of remote ICPCVD chamber configuration, in which region I is a high density plasma generation region and region III is a silicon nitride deposition region. Second, we removed the RF chuck bias power in order to minimize the possible ion bombardment generated during the silicon nitride deposition. In our remote ICPCVD, the chamber has two separated gas injectors: top gas injector (gas inlet 1) and side gas injector (gas inlet 2). The SiH$_4$ is fed through the side gas injector ring (region II). All other gases including N$_2$
enter the chamber via a top shower head in the ICP source region (region I). Source RF power at 13.56 MHz is inductively coupled into the chamber by the antenna. The magnet is used to further enhance the plasma density and to adjust the plasma profile. There is a matching box for the source RF power, so that the impedance can be matched when plasma is turned on. The temperatures in our remote ICPCVD system can be varied up to 400 °C for the chuck and up to 50 °C for the chamber wall with the RF source power up to 2500 W. We introduced cryo-pump in our remote ICPCVD system for an ultra-high-vacuum.

![Figure 1. Schematic of the remote ICPCVD chamber configuration.](image1)

We compared the characteristics of the films deposited by remote ICPCVD with those deposited by remote PECVD system, which had also been built to reduce the plasma damage in the conventional PECVD. Figure 2 shows a schematic of the remote PECVD chamber configuration used in this work.

![Figure 2. Schematic of reaction chamber of the remote PECVD.](image2)
Remote ICPCVD Silicon nitrides: film characteristics

Silicon nitride BOE (NH$_4$F : HF = 7 : 1) wet etch rate, deposition rate, and refractive index as a function of deposition parameters were constantly monitored to examine the film properties. We applied 350 watts for the ICP source RF power to minimize the damage induced by high density plasma. Through various experiments, it turned out that 350 watts is the minimum ICP source RF power to get stable ignition of N$_2$ plasma in our remote ICPCVD system.

Figure 3 shows the variation of BOE wet etch rate, deposition rate, and refractive index with the deposition temperature. The BOE wet etch rate of silicon nitride deposited by remote ICPCVD depends strongly upon the ICP source RF power and deposition temperature. The higher the ICP source RF power, the lower the BOE wet etch rate, indicating that the silicon nitride have higher density. On the other hand, the silicon nitride deposited at higher temperature exhibit higher density, indicating that the higher the deposition temperature, the more the H atoms get removed in Si-H bonding and N-H bonding. At a deposition temperature of 190 °C with ICP source RF power of 350 watts, the BOE wet etch rate of remote ICPCVD silicon nitride is approximately 120 ~ 150 Å/min, which is lower than that of remote PECVD silicon nitride (≈ 600 ~ 900 Å/min at a deposition temperature of 190 °C with source RF power of 50 watts). The deposition rate strongly depends upon the ICP source RF power but not upon the deposition temperature. The higher the ICP source RF power, the higher the deposition rate, implying that the process gas is cracked more into species by the plasma. A refractive index is the most commonly measured property of plasma-enhanced silicon nitride. It indicates the optical characteristics, which change keenly with accordance to the process parameters of remote ICPCVD. The typical values of refractive index are between 1.8 and 2.2. The increase of a refractive index with deposition temperature indicates that the deposited film becomes slightly Si-rich. This is because the high deposition temperature enables source SiH$_4$ gas to crack easily.

![Figure 3. BOE wet etch rate, deposition rate, and refractive index of remote ICPCVD silicon nitride as a function of deposition temperatures with an ICP source RF power of 350 watts.](image-url)
Residual hydrogen contents in deposited film are highly related to the electrical properties such as leakage current and breakdown field strength of the film. Hydrogen contents can be measured by Fourier transform infrared spectroscopy (FT-IR), which is a less accurate but often more convenient technique than nuclear resonance reactions [8]. This technique requires measurement of the integrated absorption peak. In this study the H contents is measured by FT-IR and evaluated by atomic %. Owing to the absence of NH$_3$ in the silicon nitride deposition, the hydrogen contents of remote ICPCVD silicon nitride film ($\approx$ 12 atomic % at the deposition temperature of 190 °C) is lower than that of remote PECVD silicon nitride film ($\approx$ 24 atomic % at the deposition temperature of 190 °C). This result confirms that the silicon nitride deposited by remote ICPCVD technique has higher density and lower hydrogen concentration than that deposited by remote PECVD.

For electrical characterization, titanium/gold (Ti/Au = 500/3500 Å) electrode with a diameter of 300 μm was evaporated by e-gun evaporator through a shadow mask to form top and bottom electrical contact of the metal-insulator-metal (MIM) structure. The silicon nitride films of 600 Å were deposited by remote ICPCVD (at a deposition temperature of 190 °C with ICP source RF power of 350 watts) and remote PECVD (at a deposition temperature of 190 °C with source RF power of 50 watts) for comparison, respectively. The DC I-V characteristics of MIM structure was measured by using HP 4155A semiconductor parameter analyzer. The electrical properties of 600 Å silicon nitride films are shown in Fig. 4. The material and electrical properties of silicon nitride film deposited by remote PECVD and remote ICPCVD with the optimized process conditions at the deposition temperature of 190°C are summarized in Table I.

Figure 4. The electrical properties of 600 Å silicon nitride films deposited by remote ICPCVD and remote PECVD.
Table I. Process conditions and silicon nitride film characteristics deposited by remote PECVD and remote ICPCVD in this study.

<table>
<thead>
<tr>
<th>Process Conditions</th>
<th>Remote PECVD</th>
<th>Remote ICPCVD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Source RF power (W)</strong></td>
<td>50</td>
<td>350</td>
</tr>
<tr>
<td><strong>Deposition temperature (℃)</strong></td>
<td>190</td>
<td>190</td>
</tr>
<tr>
<td><strong>Chamber pressure (mTorr)</strong></td>
<td>200</td>
<td>80</td>
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<tr>
<td><strong>Process gases</strong></td>
<td>He/ SiH₄/ NH₃</td>
<td>Ar/ SiH₄/ N₂</td>
</tr>
<tr>
<td><strong>Deposition rate (Å/min)</strong></td>
<td>≈ 15</td>
<td>≈ 100</td>
</tr>
<tr>
<td><strong>BOE wet etch rate (Å/min)</strong></td>
<td>600 ~ 900</td>
<td>120 ~ 150</td>
</tr>
<tr>
<td><strong>Film Stress (MPa)</strong></td>
<td>Tensile (≈275)</td>
<td>Compressive (≈140)</td>
</tr>
<tr>
<td><strong>Hydrogen contents (atomic %)</strong></td>
<td>≈ 24</td>
<td>≈ 12</td>
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<tr>
<td><strong>Breakdown Field (MV/cm)</strong></td>
<td>3.3</td>
<td>4.5</td>
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</table>

Device Fabrication and Silicon nitride Passivation

In$_{0.45}$AlAs/In$_{0.4}$GaAs MHEMT layers were grown by MBE on a GaAs substrate. A schematic cross-section of the epitaxial structure for the MHEMT is shown in Fig. 5. The metamorphic buffer consisted of a 1 μm thick linearly graded InAlAs layer with final indium contents of 50%. The active layers consisted of a 15 nm undoped In$_{0.4}$GaAs channel layer, a 4 nm In$_{0.45}$AlAs undoped spacer layer, a Si planar doping of 5 x 10$^{12}$ cm$^{-2}$, a 18 nm In$_{0.45}$AlAs undoped barrier layer, and double Si-doped In$_{0.4}$GaAs cap layers. This structure achieved a sheet carrier density of 3.4 x 10$^{12}$ cm$^{-2}$ and an electron mobility of 8,610 cm² V$^{-1}$ s$^{-1}$ at room temperature. The devices were isolated by mesa formation using wet chemical etching (H$_3$PO$_4$/H$_2$O$_2$/H$_2$O). Ge/Au/Ni/Au ohmic contacts were deposited by e-gun evaporator and alloyed by rapid thermal annealing at 300 °C for 30 s. The devices were fabricated with double recess structure for a higher breakdown performance. 100 nm T-gates were defined by e-beam lithography by using UV-5/ZEP bilayer. Selective gate recess etching was employed using a mixture of succinic acid, ammonia, and hydrogen peroxide. In order to remove the native oxide layer before gate metal deposition, the devices were exposed to Ar plasma [9]. The gate metals of Pt/Ti/Pt/Au were evaporated by using e-gun evaporator.

Device characteristics of 100 nm In$_{0.45}$AlAs/In$_{0.4}$GaAs MHEMTs before and after remote ICPCVD silicon nitride passivation were fully characterized to investigate the effects of ICP source RF power on the device performances and to examine the effects of chamber pressure on the conformality of the passivation films. In addition, the effects of refractive index on the device performances were also studied. After the gate formation, devices were fully passivated by remote ICPCVD silicon nitride with a thickness of 50 nm. The deposition temperature was maintained at 190 °C for preventing ohmic and Schottky contacts from thermal degradation. In order to evaluate the effects of remote ICPCVD passivation, we also fabricated 100 nm In$_{0.45}$AlAs/In$_{0.4}$GaAs MHEMTs passivated with remote PECVD silicon nitride for comparison.
<table>
<thead>
<tr>
<th></th>
<th>In-mole (%)</th>
<th>Thickness(Å)</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-InGaAs</td>
<td>0.40</td>
<td>100</td>
<td>$1.0 \times 10^{17}$ cm$^{-3}$</td>
</tr>
<tr>
<td>n-InGaAs</td>
<td>0.40</td>
<td>100</td>
<td>$1.0 \times 10^{18}$ cm$^{-3}$</td>
</tr>
<tr>
<td>i-InAlAs</td>
<td>0.45</td>
<td>180</td>
<td>undoped</td>
</tr>
<tr>
<td>n-planar doping</td>
<td></td>
<td></td>
<td>$5 \times 10^{12}$ cm$^{-2}$</td>
</tr>
<tr>
<td>i-InAlAs</td>
<td>0.45</td>
<td>40</td>
<td>undoped</td>
</tr>
<tr>
<td>i-InGaAs</td>
<td>0.40</td>
<td>150</td>
<td>undoped</td>
</tr>
<tr>
<td>i-InAlAs</td>
<td>0.40</td>
<td>3,000</td>
<td>undoped</td>
</tr>
<tr>
<td>i-InAlAs</td>
<td>0~0.5</td>
<td>10,000</td>
<td>Inverse step graded</td>
</tr>
</tbody>
</table>

Figure 5. Cross-section of In$_{0.45}$AlAs/In$_{0.4}$GaAs MHEMT structure on a GaAs substrate.

Results and Discussion

Optimization of Silicon nitride Passivation using remote ICPCVD

According to the previous reported results [5]-[7], significant degradation in device characteristics ($g_{m,max}$ and $I_{DS,max}$) was observed after silicon nitride passivation using conventional ICPCVD. However, for the devices passivated with remote ICPCVD silicon nitride film, we observed the improvement in device performance. Figure 6 shows the effects of ICP source RF powers varied from 350 watts to 700 watts on device performances such as $g_{m,max}$, $I_{DS,max}$, and reverse breakdown voltage ($B V_{GD}$). As shown in Fig. 6, ICP source RF power of 350 watts brought the maximum increase of $g_{m,max}$ and $I_{DS,max}$ while the $B V_{GD}$, defined at gate current ($I_g$) of -0.1 mA/mm, showed a typical drop of 1.6 V after passivation. However, the decrease of $B V_{GD}$ observed here was lower than that with silicon nitride passivation using remote PECVD (typically 3-4 V decrease after passivation). Less improvement in $g_{m,max}$ and $I_{DS,max}$ with higher ICP source RF power might be attributed to the surface property modifications induced by the high-density plasma, as evident by its dependence on the ICP source RF power. As previously mentioned, the ICP source RF power of 350 watts is the minimum ICP source RF power to get the stable ignition of N$_2$ plasma. Therefore, for passivation, the ICP source RF power was maintained at 350 watts to maximize the improvement in device performance.

Next, the effects of refractive index on device performance were studied. It is well known that device performance is critically influenced by Si/N composition ratio of silicon nitride passivation layer. Although refractive index is not used to determine exact Si/N composition ratio, it depends on the Si/N composition ratio linearly. The effects of refractive index on device performance such as $g_{m,max}$, $I_{DS,max}$, and $B V_{GD}$ for silicon nitride deposited at 190 °C with ICP source RF power of 350 watts are shown in Fig. 7. Silicon nitride passivation with a refractive index of 1.95 exhibited maximum improvement of 22 % (535 mS/mm to 654 mS/mm) in $g_{m,max}$ and maximum improvement of 20 % (551 mA/mm to 662 mA/mm) in $I_{DS,max}$ compared to those of unpassivated ones, respectively. $B V_{GD}$, defined at $I_g$ of -0.1 mA/mm, showed a relatively large drop of 2.2 V.
Figure 6. Changes of $g_{m,\text{max}}$, $I_{DS,\text{max}}$, and $BV_{GD}$ in InAlAs/InGaAs MHEMTs before and after remote ICPCVD silicon nitride passivation (refractive index = 2.0) versus ICP source RF power.

Figure 7. Changes of $g_{m,\text{max}}$, $I_{DS,\text{max}}$, and $BV_{GD}$ in InAlAs/InGaAs MHEMTs before and after remote ICPCVD silicon nitride passivation (ICP source RF power = 350 watts) versus refractive index.
However, the decrease of $BV_{GD}$ observed here is still lower than that of silicon nitride passivation using remote PECVD. These improvements of $g_{m,max}$ and $I_{DS,max}$ are presumably due to the effects of suppressed surface traps in the gate-recessed regions by silicon nitride passivation, thereby reducing the parasitic resistance [10]. As can be seen in Fig. 6 and 7, the larger improvement in $g_{m,max}$ and $I_{DS,max}$, the higher decrease of $BV_{GD}$. The more the effects of surface traps in the gate-recessed regions are suppressed with better passivation process, the more the parasitic source resistance and drain resistance are reduced. The decrease of $BV_{GD}$ after silicon nitride passivation might be attributed to the reduction of parasitic resistances. We employed the device simulation tool in order to derive the surface trap effects in the gate-recessed regions. As the surface trap density in the gate-recessed regions decreased, the $I_{DS,max}$ increased gradually [1]. These simulation results were consistent with the experimentally observed effects of silicon nitride passivation.

Silicon nitride Passivation by remote ICPCVD versus by remote PECVD

As can be seen in Table I, low deposition rate is the major problem in remote PECVD. Because of the low deposition rate, device passivation with remote PECVD silicon nitride takes much longer time than that using remote ICPCVD. In addition, the step coverage of silicon nitride layer deposited with remote PECVD is poor, causing very long deposition time to fully passivate the gate-recessed regions under the T-gate structure, which is normally employed in millimeter-wave devices. Owing to the long deposition time, thermal effects can occur during the device passivation process. For instance, a considerable positive shift of the threshold voltage ($V_{th}$) appeared after passivation with remote PECVD silicon nitride. Figure 8 shows the scanning electron microscope (SEM) image of 100 nm T-gate with remote PECVD silicon nitride layer of 120 nm and the measured DC transfer characteristics of unpassivated or silicon nitride passivated device.

![Figure 8. SEM image of 100 nm T-gate with remote PECVD silicon nitride layer (left) and DC transfer curves ($g_m$ and $I_{DS}$) of InAlAs/InGaAs MHEMT before and after remote PECVD silicon nitride passivation at a source RF power of 50 watts (right).](image)

A positive shift of $V_{th}$ after passivation indicates the gate sinking due to the thermally activated diffusion during the passivation process, which reduces the gate-to-channel distance. The thermally activated diffusion results from long deposition time.
Generally, gate sinking during the passivation process results in the increase of $g_{m,\text{max}}$ and the decrease of $I_{DS,\text{max}}$ [11]. However, as can be seen in Fig. 8, the slight increase of $I_{DS,\text{max}}$ was observed after passivation, although the gate sinking occurred during the passivation. This result might indicate that the increases of $g_{m,\text{max}}$ and $I_{DS,\text{max}}$ are related with both the reduction of parasitic resistances and the gate-sinking effect. Even though some device performances such as $g_{m,\text{max}}$ and $I_{DS,\text{max}}$ was improved by passivation with remote PECVD silicon nitride, the considerable reduction of $BV_{GD}$ and the shift of $V_{th}$ can bring the problems in power performance and manufacturability issue.

Figure 9 shows the SEM image of 100 nm T-gate with a remote ICPCVD silicon nitride layer of 50 nm and the measured DC characteristics before and after silicon nitride passivation. As shown in Table I, the deposition rate of remote ICPCVD is much higher than that of remote PECVD. In addition, the step coverage of silicon nitride layer using remote ICPCVD is much better than that of remote PECVD. For instance, to deposit silicon nitride layer of approximately 20 ~ 25 nm on the gate-recessed regions, only total of 50 nm deposition is needed by remote ICPCVD, while in case of remote PECVD, 120nm deposition is needed. Because of large deposition rate and good step coverage, the process time for passivation is greatly reduced in remote ICPCVD. Consequently, thermal effects such as a positive shift of $V_{th}$ due to the gate sinking did not take place after passivation with remote ICPCVD silicon nitride. Instead, the slight negative shift of $V_{th}$ occurred after passivation with remote ICPCVD silicon nitride, which might be due to the reduction of the surface traps in the gate-recessed regions.

![Figure 9. SEM image of 100 nm T-gate with remote ICPCVD silicon nitride layer (left) and DC transfer curves ($g_m$ and $I_{DS}$) of silicon nitride passivated and unpassivated device at ICP source RF power of 350 watts (right).](image)

**DC and RF characteristics with Silicon nitride Passivation using remote ICPCVD**

The DC drain current-voltage curves and the forward/reverse gate Schottky diode characteristics before and after remote ICP passivation with an ICP source RF power of 350 watts are shown in Fig. 10. The soft knee-voltage was reduced after passivation. This implies that the parasitic source resistance is reduced due to the suppression of surface traps in the gate-recessed regions after passivation. Generally, the reverse gate leakage current becomes relatively large and the forward gate turn-on voltage is reduced after passivation with remote PECVD silicon nitride. On the contrary,
after passivation with remote ICPCVD silicon nitride, the changes of forward diode characteristics (i.e., ideality factor and gate turn-on voltage) were minimal while the reverse gate leakage current was slightly increased. These results indicate that the impact of plasma to InAlAs surface is different between remote PECVD and remote ICPCVD.

![Figure 10. DC drain I-V curves (left) and forward/reverse gate Schottky diode characteristics (right) of 100 nm InAlAs/InGaAs MHEMT before and after remote ICPCVD silicon nitride passivation.](image)

The effects of remote ICPCVD silicon nitride passivation on the RF performance of the InAlAs/InGaAs MHEMTs were also examined. In our investigation, the RF measurement was performed after double layer passivation for better reliability. The insulator with high dielectric strength and high mechanical strength is preferred for the final passivation layer for better hermeticity and reliability of devices [12]. It is well known that increased refractive index with Si-rich composition reduces the BOE etch rate of the films [13]. We also confirmed that the BOE etch rate of the Si-rich films is lower than that of the N-rich films. This implies that the Si-rich film is much denser than the N-rich film. However, based on the results of Fig. 7, the devices with the passivation silicon nitride having refractive index of 1.93~1.95, that is, N-rich film, yielded the most excellent performance. Based on these results, InAlAs/InGaAs MHEMTs with a gate length of 100 nm were passivated by double layer silicon nitrides, the first 30 nm-thick silicon nitride film with a refractive index of 1.95, followed by the second 60 nm-thick silicon nitride film with a refractive index of 2.05. In other words, the first nitride layer is optimized for the enhancement of device performance and the denser second nitride layer is deposited to protect the devices from non-hermetic environment. The denser nitride film would be suitable for a barrier to moisture and mobile ions.

There was no difference in device DC performance between the devices with one layer and with double layer passivation. Figure 11 shows the SEM image of 100 nm T-gate with double silicon nitride layers of 30/60 nm and the RF performance of double layer passivated device with remote ICPCVD silicon nitride. Small-signal S-parameters were measured from 0.5 to 50 GHz. It showed $f_T$ of 200 GHz at drain voltage ($V_{DS}$) of 1 V and gate voltage ($V_{GS}$) of -0.2 V extrapolated from the current gain ($H_{21}$) and $f_{max}$ of 280 GHz at $V_{DS}$ of 2 V and $V_{GS}$ of -0.2 V extrapolated from the maximum available gain (MAG). It should be noted that excellent RF performance of passivated device resulted from the improvement of DC characteristics such as $g_{m,max}$ and $I_{DS,max}$ due to the
reduction of parasitic resistances caused by the excellent passivation process with remote ICPCVD.

Figure 11. SEM image of 100 nm T-gate with double silicon nitride layers of 30/60 nm (left) and RF characteristics of 2 x 50 μm double layer passivated InAlAs/InGaAs MHEMTs with remote ICPCVD silicon nitride.

Conclusions

In this study, a new remote type ICPCVD system (HiDep) was developed by BMR Technology Corporation to minimize the damage induced by high density plasma. First, the characteristics of silicon nitride films deposited by remote ICPCVD have been investigated and then novel nitride passivation using remote ICPCVD has been successfully demonstrated on 100 nm T-gate In_{0.45}AlAs/In_{0.4}GaAs MHEMTs with minimal damage. SiH₄/N₂ process gases are used in remote ICPCVD for silicon nitride deposition instead of SiH₄/NH₃ chemistries in remote PECVD to reduce the hydrogen contents. The silicon nitride films with remote ICPCVD exhibited higher quality, higher density, and lower hydrogen concentration than silicon nitride films deposited by remote PECVD. The passivated devices with remote ICPCVD silicon nitride showed considerable enhancement on DC characteristics such as a $g_{m,max}$ and an $I_{D,S,max}$ with excellent RF performance such as a $f_T$ of 200 GHz and an $f_{max}$ of 280 GHz. InAlAs/InGaAs MHEMT with the excellent characteristics might be potentially useful for high-performance MMIC applications such as 77 GHz automotive radars. The results achieved in this work show that the silicon nitride using remote ICPCVD is a suitable candidate for the next-generation passivation technique for InAlAs/InGaAs MHEMT.

Acknowledgments

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