Millimeter-wave GaN HEMTs with Cavity-gate Structure Using MSQ-based Inter-layer Dielectric

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Abstract

We have fabricated millimeter-wave GaN high electron mobility transistors (HEMTs) using methyl silsesquioxane (MSQ)-based inter-layer dielectric to suppress current collapse by enhancing the moisture resistance, and removed MSQ around the gate electrode for reducing parasitic capacitance. We clarified that the moisture resistance of conventional benzocyclobutene (BCB) is insufficient to suppress current collapse because water molecules easily permeate BCB, especially when using a cavity-gate structure. On the other hand, in the case of hydrophobic MSQ, the moisture resistance was improved by using a cavity-gate structure, and the current collapse due to moisture was effectively suppressed. So, improving the moisture resistance with hydrophobic low-k films plays a key role in reducing the current collapse of GaN HEMTs with a cavity-gate structure. Moreover, the parasitic capacitance of GaN HEMTs was successfully reduced by using the MSQ-cavity, and RF performance was improved by around 20%.

INTRODUCTION

GaN high electron mobility transistors (HEMTs) have demonstrated prominent performance in high-power applications, such as power amplifiers in wireless base stations and radar systems [1]. These amplifiers are also expected to be used for high data-rate wireless communication using millimeter-wave [2]. The requirements for millimeter-wave amplifiers include a large drain current to achieve a high level of power and efficiency, and high reliability to ensure high power operations. Therefore, GaN HEMTs are promising for use in millimeter-wave amplifiers because of their high 2DEG density and high breakdown voltage. However, the phenomenon called current collapse has been reported as an issue with GaN HEMTs [3-4]. It is considered that current collapse is caused by electron traps at the surface of GaN HEMTs, and one of the possible origins for electron traps is moisture because of the ionization of water molecules [5]. Especially in the case of millimeter-wave applications, current collapse increases with short gate-length due to a high electric field at the gate edge. Moreover, passivation films such as silicon nitride must be kept thin because of their high dielectric constant to reduce the parasitic capacitance in monolithic microwave integrated circuits (MMICs) [6-7]. Thus, it is difficult to prevent water molecules from adhering to the surface of GaN HEMTs when using silicon nitride. Therefore, a low dielectric constant (low-k) inter-layer dielectric is necessary in millimeter-wave MMICs, and carbon-based low-k films such as benzocyclobutene (BCB) are often used in MMIC interconnects [8-9]. Furthermore, process technology was developed for InP HEMTs to remove BCB around the gate electrode for decreasing parasitic capacitance by a cavity-gate structure [10]. This structure is effective to improve the operating speed of InP HEMTs without causing any performance degradation. However, in the case of GaN HEMTs, the moisture resistance of BCB is insufficient to suppress current collapse because of its hydrophilic surface (Fig. 1 (a)). On the other hand, methyl silsesquioxane (MSQ)-based materials are good candidates for low-k films to improve moisture resistance because of their hydrophobic property (Fig. 1 (b)), with a large amount of methyl group's as shown in Fig. 2 [11]. In this paper, we report the fabrication of millimeter-wave GaN HEMTs with a cavity-gate structure using MSQ, and demonstrate improved RF performance without current collapse.

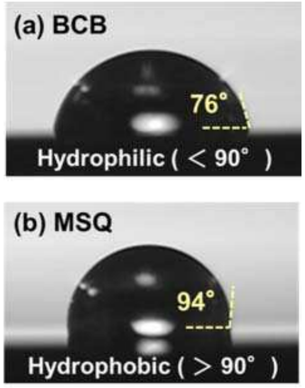

Fig. 1. Comparison of water contact angle between BCB (a) and MSQ (b).

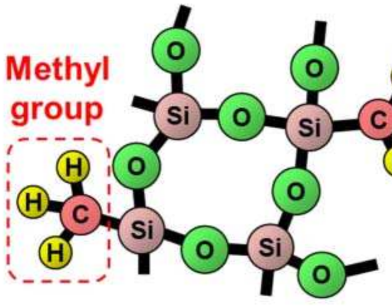

Fig. 2. Schematic illustration for the chemical structure of MSQ-based low-k films.

EXPERIMENTAL

We have fabricated 0.1 µm gate length AlGaN/GaN HEMTs with cavity-gate structure using MSQ (MSQ-cavity) as shown in Fig. 3. MSQ was deposited by using a spin-coat method, and cured in a nitrogen atmosphere for 30 min. at 250°C. The dielectric constant of MSQ is 2.7. Before MSQ deposition, the gate electrode was selectively covered by a sacrificial filling material that was removed through the MSQ after deposition. Therefore, the gate cavity was surrounded by MSQ without exposure to the air.

Then, the current collapse was evaluated by decreasing the drain-to-source current (I_{ds}) due to pinched-off bias stress (V_{gs} = -3 V, V_{ds} = 20 V) from pulsed I_{ds} - V_{ds} characteristics at a relative humidity (RH) of 50%. The pulse width and separation were 1 µs and 1 ms, respectively. The current collapse was quantified by the ratio of I_{ds} with bias stress to I_{ds} without bias stress at a V_{ds} of 5 V. Furthermore, to investigate the effect of the cavity-gate structure on moisture resistance, the current collapse due to humidification was evaluated by using 100°C water vapor. The relationship between humidification time and current collapse was compared with a conventional BCB-cavity. Then, the parasitic capacitance and RF performance of the AlGaN/GaN HEMTs using a MSQ-cavity were calculated from small-signal S-parameters.

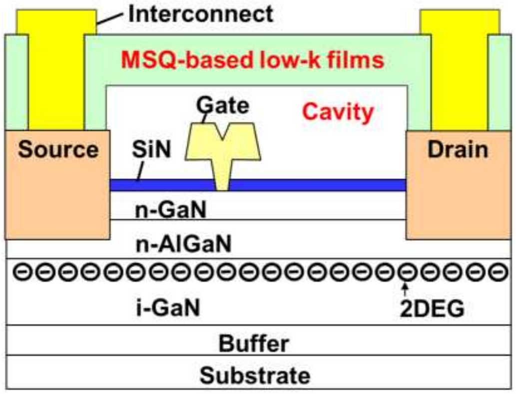

Fig. 3. Schematic cross-sectional view of GaN HEMTs used in this work.

RESULTS AND DISCUSSIONS

Figure 4 shows the current collapse of AlGaN/GaN HEMTs using conventional BCB encapsulation (a), and that with a BCB cavity-gate structure (b). The current collapse was quantified by the ratio of I_{ds} with bias stress to I_{ds} without bias stress at a V_{ds} of 5 V. As shown in these figures, the current collapse of AlGaN/GaN HEMTs deteriorated with a BCB cavity-gate structure compared to BCB encapsulation. It is considered that the moisture resistance of BCB was degraded by using the cavity-gate structure due to the decreased thickness of BCB over the gate. For this reason, water molecules in the air (RH = 50%) could easily approach the surface of AlGaN/GaN HEMTs and cause current collapse when using BCB cavity-gate structure. On the other hand, as shown in Fig. 5, the current collapse when using MSQ was unchanged in spite of using a MSQ cavity-gate structure. It is suggested that the moisture resistance of MSQ is not degraded if the film thickness decreases when using cavity-gate structure, because of the excellent hydrophobic property of MSQ.

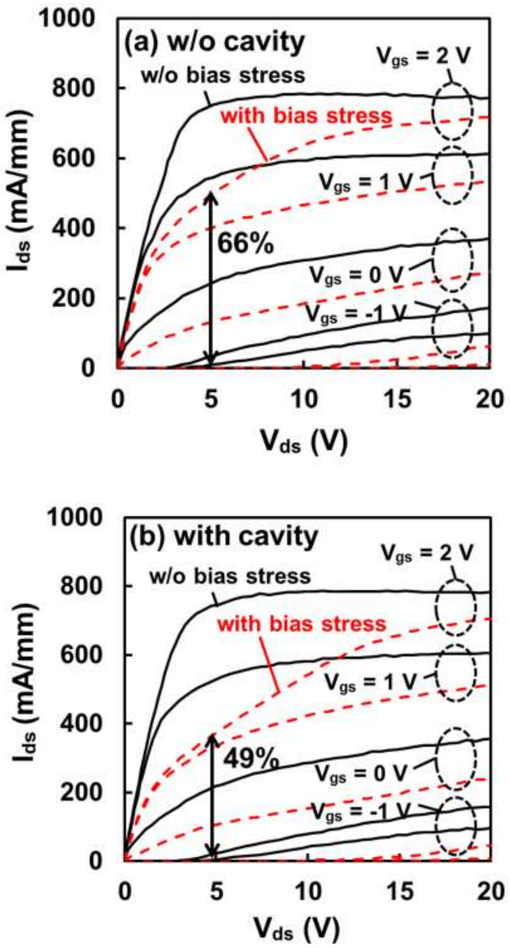

Fig. 4. Current collapse of GaN HEMTs when using conventional BCB encapsulation (a) and that with a BCB cavity-gate structure (b).

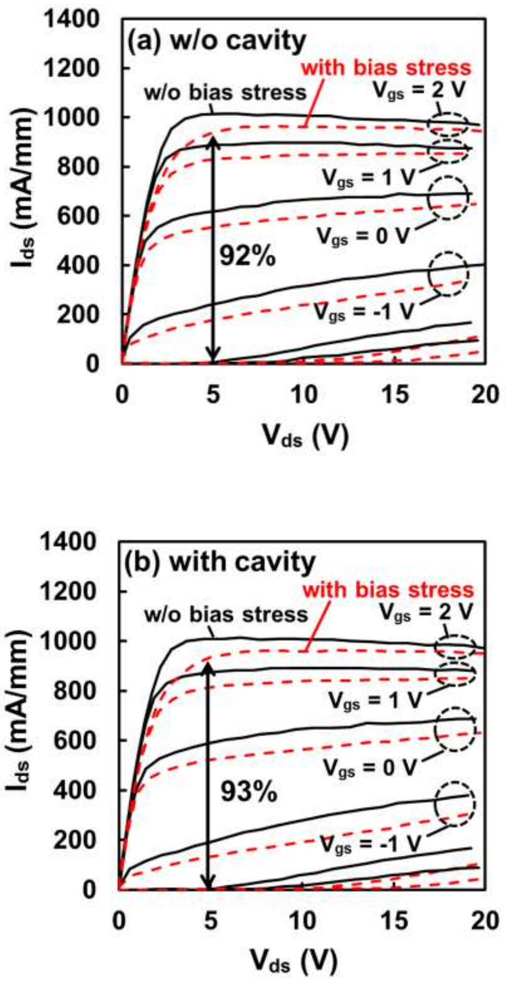

Fig. 5. Current collapse of GaN HEMTs when using MSQ encapsulation (a) and that with a MSQ cavity-gate structure (b).

Then, to clarify the effect of cavity-gate structure on the moisture resistance, we have evaluated the current collapse due to humidification by using 100°C water vapor. Figure 6 shows the relationship between humidification time and the ratio of I_{ds} with bias stress to I_{ds} without bias stress when using a cavity-gate structure of BCB or MSQ. As shown in Fig. 6, the current collapse of the BCB-cavity increased with an increase in humidification time. On the other hand, the I_{ds} of MSQ-cavity was constant in spite of increasing humidification time. From these results, it was clarified that improving the moisture resistance with MSQ is effective in suppressing the current collapse of AlGaN/GaN HEMTs with cavity-gate structure.

Figure 7 shows our proposed mechanism for current collapse of AlGaN/GaN HEMTs due to moisture when using a cavity-gate structure. Figure 7 (a) shows moisture uptake through the surface of low-k films when using hydrophilic BCB. In this case, the moisture resistance of BCB was degraded by using cavity-gate structure due to the decreased thickness of BCB over the gate. Therefore, water molecules can easily permeate through low-k films, and approach the surface of AlGaN/GaN HEMTs. Then, water molecules are ionized by bias stress, and electrons are captured by ions [11]. So, the I_{ds} decreases with humidification by current collapse. On the other hand, as shown in Fig. 7 (b), moisture uptake is suppressed when using hydrophobic MSQ. In this case, the moisture resistance of MSQ is not degraded if the film thickness decreases when using a cavity-gate structure because of excellent hydrophobic property. Therefore, the I_{ds} is constant in spite of humidification because water molecules could not approach the surface of AlGaN/GaN HEMTs. So, improving the moisture resistance with hydrophobic low-k films plays a key role in reducing current collapse of AlGaN/GaN HEMTs, especially when using a cavity-gate structure.

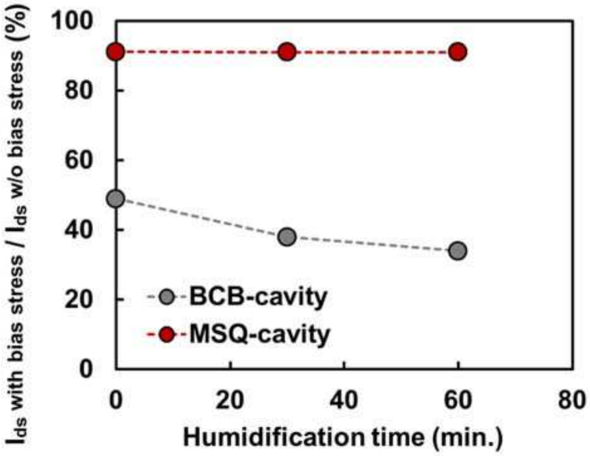

Fig. 6. Relationship between humidification time and current collapse of GaN HEMTs when using BCB-cavity and MSQ-cavity.

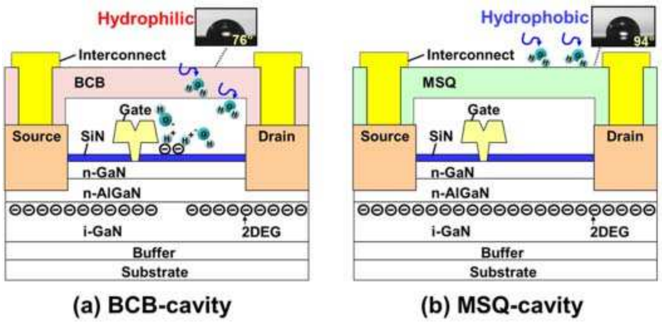

Fig. 7. Schematic cross-sectional view of the proposed mechanism for current collapse of GaN HEMTs due to moisture when using BCB-cavity (a) and MSQ-cavity (b)

Then, to investigate the effect of a MSQ-cavity on the parasitic capacitance of AlGaN/GaN HEMTs, gate-to-source (C_{gs}) and gate-to-drain capacitance (C_{gd}) were calculated from small signal S-parameters. As shown in Fig. 8, C_{gs} and C_{gd} were successfully reduced by around 20% by using a MSQ-cavity. According to previous reports [10], if we use BCB which has the same dielectric constant of MSQ ($k = 2.7$), C_{gs} and C_{gd} will increase around 20% after BCB deposition. Therefore, it is considered that the parasitic capacitance of the MSQ-cavity is the same as that without MSQ (before MSQ deposition). Furthermore, we calculated the cutoff frequency (f_T) and oscillation frequency (f_{max}) of AlGaN/GaN HEMTs to evaluate RF performance. As shown in Fig. 9, f_T and f_{max} were improved around 20% by using MSQ-cavity. This value was in agreement with the results of the parasitic capacitance. From these results, it is clarified that a MSQ-cavity is effective to improve RF performance by a dramatic reduction in parasitic capacitance.

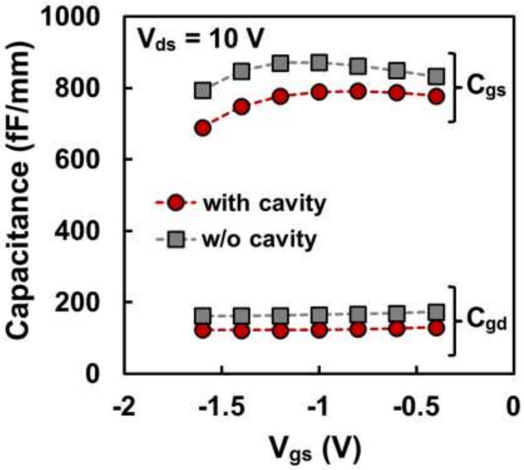

Fig. 8. Parasitic capacitances of GaN HEMTs when using a MSQ-cavity.

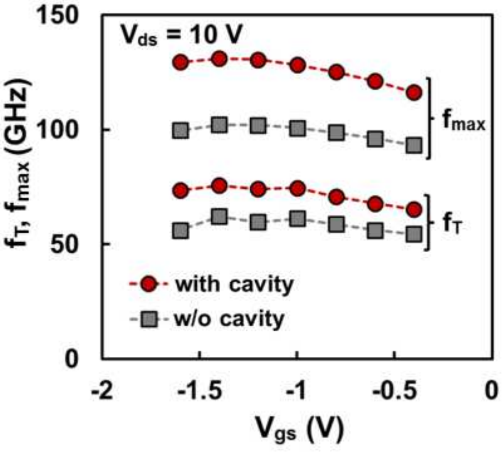

Fig. 9. RF performance of GaN HEMTs when using a MSQ-cavity.

CONCLUSIONS

We have fabricated millimeter-wave GaN HEMTs using a MSQ-cavity to improve RF performance without the current collapse. We clarified that the moisture resistance of conventional BCB is insufficient to suppress current collapse because of its hydrophilic property. Therefore, the moisture resistance was degraded by using a BCB cavity-gate structure, due to the decreased thickness of BCB over the gate. On the other hand, in the case of hydrophobic MSQ, the moisture resistance was not degraded by using a cavity-gate structure, and the current collapse due to moisture was effectively suppressed. So, improving the moisture resistance with hydrophobic low-k films plays a key role in reducing the current collapse of GaN HEMTs with a cavity-gate structure. Moreover, the parasitic capacitance of GaN HEMTs was successfully reduced by using a MSQ-cavity, and RF performance was improved by around 20%. We conclude that a MSQ-cavity is a good candidate for low-k interconnects used in millimeter-wave GaN HEMTs.

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ACRONYMS

HEMT: High Electron Mobility Transistor
MMICs: Monolithic microwave integrated circuits
Low-k: Low dielectric constant
MSQ: Methyl silsesquioxane
BCB: Benzocyclobutene