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1 W/mm Output Power Density for H-Terminated Diamond MOSFETs With Al_2O_3/SiO_2 Bi-Layer Passivation at 2 GHz

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ABSTRACT We have demonstrated a novel method of depositing ALD-Al_2O_3/PECVD-SiO_2 bi-layer dielectric to passive the surface channels of the hydrogen-terminated diamond (H-diamond). After Al_2O_3/SiO_2 passivation, the surface current increased with time and then tended to be saturated. Afterwards, it became much more stable and showed a larger current than an unpassivated counterpart. The H-diamond MOSFETs were fabricated by using this bi-layer passivation structure and an extremely low Ohmic contact resistance of 0.87 Ω·mm was obtained. The H-diamond RF MOSFET with gate length of 0.45 μm achieved a high current density of −549 mA/mm and an extrinsic f_T/f_{max} of 15/36 GHz. By load-pull measurement, a high output power density of 1.04 W/mm was obtained at frequency of 2 GHz. The results reveal that it is a promising solution for high-stable and high-power diamond transistors by using the Al_2O_3/SiO_2 bi-layer passivation.

INDEX TERMS H-diamond, bi-layer passivation, output power.

I. INTRODUCTION

Since the first hydrogen-terminated diamond (H-diamond) transistor was born in 1994, the H-diamond has attracted more and more attentions to develop high performance RF transistors for its remarkable properties such as high concentration of two dimensional hole gas (2DHG), large critical breakdown electric field of 10 MV/cm, as well as high thermal conductivity of 22 $W{\cdot}cm^{-1}{\cdot}K^{-1}$ [1]–[3]. Although some breakthroughs have been realized, the performances of the H-diamond transistors are still far from expected [4]–[9]. One of the most important reasons is that the large surface resistance caused by its low 2DHG mobility has limited their performances [10]. In addition, the H-diamond transistors, especially those fabricated by using a self-aligned process, always suffer from instabilities for lack of effective passivation layers [11]. Therefore, it is essential to introduce a reliable dielectric to passivate the channels well and meanwhile sustain a low surface resistance.

The Al_2O_3 is the most widely researched to passivate the 2DHG channels for its high reliability and low damage on the C-H bonds [12]–[14]. SiO_2 is also an excellent passivation material with some properties superior to Al_2O_3. For example, SiO_2 has a much lower permittivity than Al_2O_3, which is beneficial to reduce the parasitic capacitances. SiO_2 shows a stronger acid and alkali resistance than Al_2O_3, which can protect the device well in some harsh environments. The growth rate of SiO_2 by plasma enhanced chemical vapor deposition (PECVD) is much larger than ALD-deposited Al_2O_3, which contributes to a high yield. However, PECVD-deposited SiO_2 was rarely reported to passivate the H-diamond for it would damage the C-H bonds during deposition.

To solve this problem, we have proposed a novel ALD-Al_2O_3/PECVD-SiO_2 bi-layer structure to passivate the H-diamond transistors in this work. The lower thin Al_2O_3 is used as the gate insulator and the first passivation layer, which can protect the C-H bonds from being damaged during SiO_2 deposition. The upper thick SiO_2 encapsulating the gates is used as the second passivation layer, which can further protect the 2DHG channels and minimize the impacts of the surface states. By characterizing the surface current of the H-diamond, it was observed that although the current significantly dropped immediately after Al_2O_3/SiO_2 deposition, it would gradually restore to a high level and then become much sable than an unpassivated counterpart. The H-diamond MOSFETs with Al_2O_3/SiO_2 bi-layer passivation were fabricated and high performances were achieved. It indicates that using Al_2O_3/SiO_2 bi-layer passivation is a promising solution for high-stable and high-power H-diamond transistors.

II. DEVICE FABRICATION

The H-diamond MOSFETs were fabricated on a 5×5×0.3 mm^3 CVD (100)-oriented single crystal diamond substate. The surface hydrogenation was carried out in a microwave plasma chemical vapor deposition (MPCVD) system (OptoSystem ARDIS-300) to generate 2DHG channels. The hydrogenation temperature, power and time were 700 °C, 2.2 kW, and 10 min, respectively. After hydrogenation, the surface roughness was measured to be less than 1.0 nm by an atomic force microscope.

The schematic cross-section structure and the photo of the H-diamond MOSFET are shown in Figs. 1(a) and (b). The device fabrication began with depositing a thin Au film of about 50 nm on the diamond surface to form ohmic contacts by electron beam (EB) evaporation. The source, drain and channel regions were protected by the photoresist. The unmasked Au was removed in the potassium iodide (KI) solution. Device electrical isolation was achieved by exposing the surface to a low power oxygen plasma for 5 min. The source to drain spacing was defined by the second photolithography. The source and drain electrodes were separated by wet etching in the KI solution and a very smooth edge morphology was realized. After removing the photoresist, the substrate was annealed in the ALD chamber at a high temperature of 350 °C for 10 min to remove the adsorbates from the surface. Subsequently, a 50 nm thick Al_2O_3 gate dielectric was deposited by ALD at the same temperature. The trimethylaluminum and deionized water were used as the reactants. The gate windows were defined by the EB lithography and a 20/500 nm Ti/Au was deposited as the gate metals by EB evaporation. After the gates were fabricated, a 200 nm SiO_2 was deposited as the second passivation layer by PECVD at 280 °C. Finally, another 20/500 nm Ti/Au metal stack was deposited as the test pads after the Al_2O_3/SiO_2 windows were opened. The gate length L_G, gate to source spacing L_{GS}, and gate to drain spacing L_{GD} were measured as 0.45 μm, 0.7 μm and 1.8 μm, respectively, as shown in the SEM image in Fig. 1(c).

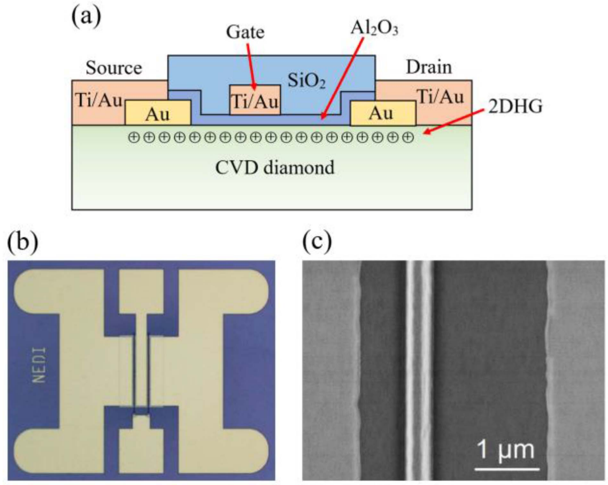

FIGURE 1. **(a) The schematic cross-section structure, (b) optical microscope photo, and (c) enlarged SEM image of the H-diamond MOSFET.**

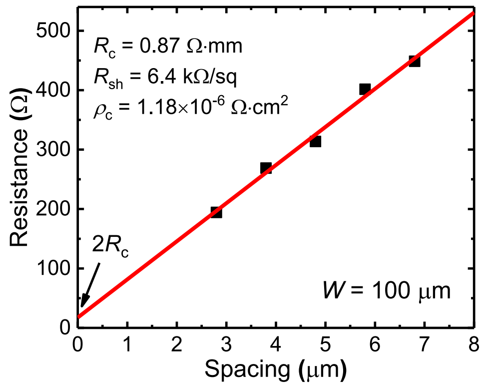

FIGURE 2. **The TLM measurement results of the Au/H-diamond Ohmic contacts.**

III. RESULTS AND DISCUSSION

All the direct current characteristics were conducted by using an Agilent B1500A system. After the ohmic electrodes were realized, the ohmic contact resistance was characterized by using a transmission line method (TLM), as the result shown in Fig. 2. To improve the accuracy of the results, the electrode spacings were measured precisely by SEM. The contact resistance R_c was calculated to be as low as 0.87 Ω·mm, which is the lowest value achieved on a H-diamond surface. The sheet resistance R_{sh} of the 2DHG channel was 6.4 kΩ/sq and the specific contact resistance ρ_c was 1.18×10^{-6} Ω·cm^2, indicating the surface was hydrogenated well and an excellent ohmic contact was obtained.

The surface current of the H-diamond with time was measured by using an ungated structure with a channel length of 3 μm and width of 100 μm, as the measurement schematic and results shown in Fig. 3. The initial current of the channel exposed to air was measured to be 48.7 mA at a voltage of

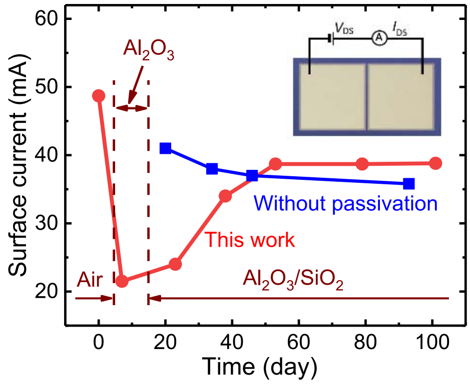

FIGURE 3. The surface current of the ungated structure with a channel length of 3 μm and width of 100 μm versus the time.

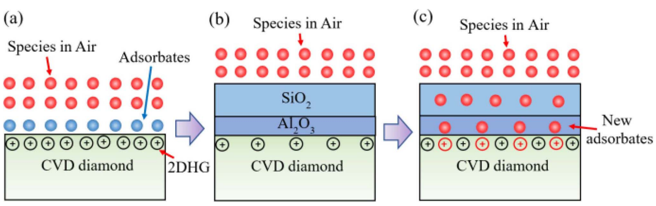

FIGURE 4. The models of the formation of H-diamond surface holes (a) before Al_2O_3 deposition, (b) immediately after Al_2O_3/SiO_2 deposition, and (c) 60 days after Al_2O_3/SiO_2 deposition.

10 V. After deposition of the Al_2O_3 by ALD, the current significantly dropped to 21.5 mA as the 2DHG concentration deceased with the desorption of its surface adsorbates, as the models shown in Figs. 4(a) and (b). It is consistent with the surface transfer doping theory [3], [15]. After deposition of the second passivation layer of SiO_2 by PECVD, the current was slightly increased to 24.0 mA, suggesting that 50 nm Al_2O_3 is thick enough to protect the channels from being damaged during PECVD. The current was further increased to 34.0 mA after 15 days and saturated at 38.7 mA after 30 days. We assume that the restore of the current is mainly related to the improvement of the 2DHG concentration as some species in air penetrated into the dielectric and reached the H-diamond/Al_2O_3 interface to produce new adsorbates, as the models shown in Figs. 4(b) and (c). Similar phenomenon was also observed on the H-diamond with an Al_2O_3-SiO_2 mixed film [16]. Passivated by the mixed film, the surface resistance was constant at a high level when kept in N_2 atmosphere, while decreased quickly and tended to be saturated in 1~3 days once exposed to air. It was assumed that the O_2 in air enhanced the surface conductance. In this work, the current increased very slowly and it took a much longer time period to be saturated. It was mainly due to its much thicker SiO_2 passivation layer, which reduced the penetration efficiency of the species. In the next 50 days, no obvious change in current was observed. We assume that the density of the species which reached the interface was saturated and then the surface current was constant at a high level. The current of an unpassivated channel with time was

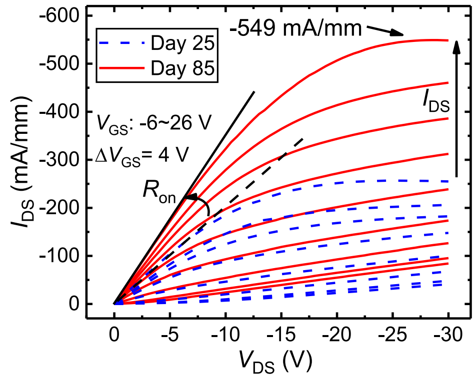

FIGURE 5. The direct current output characteristics of the H-diamond RF MOSFET with gate length of 0.45 μm.

measured for a comparison and the result is also plotted in Fig. 3. Although the initial current of the unpassivated channel was much larger than that passivated by Al_2O_3/SiO_2, it was not stable and decreased with time. In about 17 days later, the current became smaller than that with Al_2O_3/SiO_2 passivation. It implies that using the Al_2O_3/SiO_2 bi-layer passivation can greatly improve the stability of the 2DHG channels and achieve a high surface current, which is of importance for the device applications.

The direct current output characteristics of the H-diamond MOSFET with gate length of 0.45 μm was measured at V_{DS} of −30 V, as shown in Fig. 5. Soon after the device was fabricated (on day 25), the maximum current density I_{DS} was −256 mA/mm and the on-resistance R_{on} was as large as 47 Ω·mm. After 60 days (on day 85), when the surface current was saturated, the current density of the H-diamond MOSFET was significantly increased to −549 mA/mm and the on-resistance was reduced to 28 Ω·mm, which exhibits advanced performances than that passivated by the Al_2O_3-SiO_2 mixed film [16]. It indicates that the direct current performances were dramatically improved with the increase of the surface conductance. It is observed that the device cannot pitch off well even at a very large positive gate voltage of 26 V owing to its severe short channel effects. To prove it, the direct current characteristics of a long channel MOSFET with gate length of 50 μm fabricated on the same substrate were measured, as the results shown in Fig. 6. It was observed in the I_{DS}-V_{DS} curves that the device pitched off well at V_{GS} = 1 V and showed a maximum current density of −16.1 mA/mm at V_{GS} = −8 V. A much lower threshold voltage of about 1 V and a sub-threshold swing of 188 mV/dec were obtained from the transfer curves. The on/off ratio was higher than 10^8. It implies that the bad pitch-off and the shift of the threshold for the device with gate length of 0.45 μm originate from its severe short channel effects.

The small signal characteristics of the H-diamond MOSFET with gate length of 0.45 μm were measured on an 8510B network analyzer after the surface current was saturated. An extrinsic current gain cutoff frequency f_T of

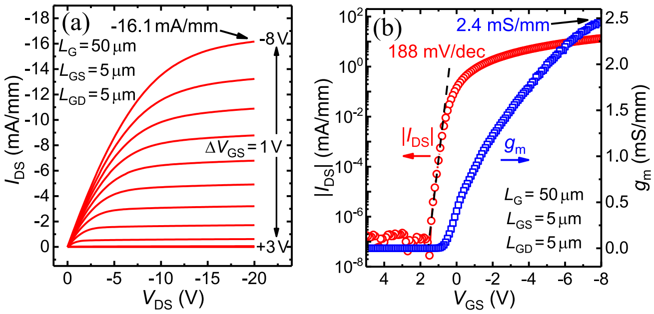

FIGURE 6. (a) The direct current output characteristics and (b) the transfer characteristics of the H-diamond MOSFET with gate length of 50 µm.

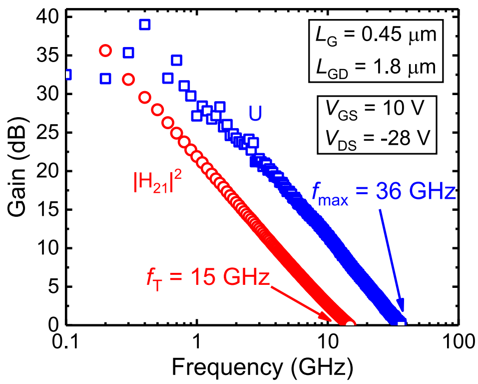

FIGURE 7. The RF small signal characteristics of the H-diamond RF MOSFET with L_G of 0.45 µm.

15 GHz and maximum frequency of oscillation f_{max} of 36 GHz were obtained at $V_{GS} = 10$ V and $V_{DS} = -28$ V, as shown in Fig. 7. The f_{max}/f_T ratio is as high as 2.4 for its low gate resistance realized by a thick gate metal stack of 520 nm. According to the relationship between f_T and gate length L_G, the saturation velocity was calculated to be 4.24×10^6 cm/s, which is quite similar to 4.4×10^6 cm/s reported in our previous work [6], [17]. It indicates that the saturation velocity of the 2DHG would not deteriorate after deposition of the Al_2O_3/SiO_2 bi-layer passivation.

The RF power output performances of the H-diamond MOSFET were measured at frequency of 2 GHz in continuous wave mode by using a load-pull setup. The device was biased at $V_{DS} = -28$ V and $V_{GS} = 15$ V, as the result shown in Fig. 8. A high output power density of 1.04 W/mm has been achieved with associated gain of 3.22 dB and power added efficiency (PAE) of 13.69%. To the best of our knowledge, it is the largest output power density achieved at 2 GHz for a diamond transistor so far [8], [18], [19]. It indicates that the Al_2O_3/SiO_2 bi-layer passivation is suitable for high power H-diamond transistors.

IV. CONCLUSION

A novel ALD-Al_2O_3/PECVD-SiO_2 bi-layer dielectric has been demonstrated to passivate the surface channels of the H-diamond substrate. Although the surface current degraded significantly immediately after dielectric deposition, it was

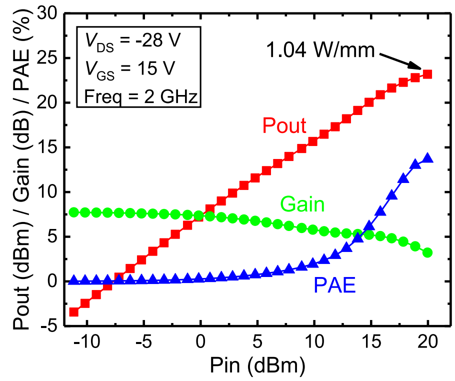

FIGURE 8. The RF power output characteristics at 2 GHz of the H-diamond RF MOSFET with L_G of 0.45 µm.

observed that the current increased with time and then tended to be saturated. When the surface current was saturated, it became much more stable and even showed a larger current than an unpassivated counterpart. The H-diamond MOSFETs were fabricated by using this new passivation technique. An extremely low Ohmic contact resistance of 0.87 Ω·mm was obtained, which is the lowest value achieved on H-diamond. When the surface current was saturated, the device with gate length of 0.45 µm demonstrated a high current density of −549 mA/mm and an extrinsic f_T/f_{max} of 15/36 GHz. The RF output characteristics were measured at frequency of 2 GHz and a high output power density of 1.04 W/mm has been achieved, which is the highest value for a diamond transistor operating at 2 GHz. It implies that using Al_2O_3/SiO_2 bi-layer dielectric can passive the 2DHG channel well and it is a promising method to fabricate high frequency and high-power, as well as highly stable H-diamond transistors.

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