# DIAMOND COATED ALGAN/GAN HIGH ELECTRON MOBILITY TRANSISTORS - EFFECT OF DEPOSITION PROCESS ON GATE ELECTRODE

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**Abstract**

We studied the influence of the diamond deposition on the degradation of Schottky gate electrodes (i.e. Ir or $IrO_2$) and on the electrical characteristics of AlGaN/GaN high electron mobility transistors (HEMTs). Thermally stable Schottky gate electrodes are necessary to withstand high temperatures and aggressive conditions (>95% hydrogen-containing plasma) during diamond chemical vapour deposition (CVD) process. In present study, the diamond films were selectively deposited on the AlGaN/GaN circular HEMT by focused (ellispoidal cavity reactor) and linear antenna (surface wave) microwave plasma at different temperatures from 400°C to 1100°C. The preliminary results on electrical measurements on the diamond-coated c-HEMTs showed degraded electrical properties comparing to c-HEMTs before deposition process, which was attributed to degradation of the Ir gate electrodes even at temperatures as low as 400°C. On the other hand, metal oxide gate electrode layer ($IrO_2$) can withstand diamond CVD process even at high temperatures (~900°C) which make it suitable for fabrication of all-in-diamond c-HEMT devices for high-power applications.

**Keywords:** GaN HEMT, CVD diamond, iridium oxide, thermal stability, IV characteristics

## 1. INTRODUCTION

High temperature (HT) stable electronic devices potentially working in harsh environments have been currently investigated. They are important not only for safety and aerospace research but also for research in different industrial sectors. Recently, the fabrication technology of Si based devices is currently well developed, but the mechanical, chemical, thermal and electronic properties of Si are limited. Only wide bandgap semiconductors like SiC, group of III-Nitrides (III-N) or diamond are capable to work in extreme conditions. In the case of GaN-based field effect transistors (FETs) of high performance or working at high temperatures, the highly efficient thermal management has to be solved in order to suppress the self-heating effect of the device [1-2].

The heat dissipation strongly affects the device characteristics. It was shown that in the AlGaN/GaN heterostructures the thermal impedance is strongly determined by the substrate material. Recently, instead of sapphire and Si (which are commonly used as the substrates for AlGaN/GaN devices and have thermal conductivity of 0.34 and 1.3 W/cmK), the use of SiC or single-crystalline diamond (SCD) substrates with thermal conductivity of 3.50 and 23 W/cmK, respectively, are preferred [3]. Both SiC and SCD substrates in combination with the AlGaN/GaN heterostructures make these devices favorable for high-power electronic applications [3]. However, SCD substrates of reasonable dimensions are very limited and still too expensive. Therefore, the trend is to grow diamond films on GaN without deteriorating its electronic properties. The diamond films can act as a passivation layer, a functional absorption layer or as a stress engineered layer due to different thermal expansion coefficients of diamond and GaN [4].

One of the most important factors in enhancing the electrical performance of AlGaN/GaN HEMT is the formation of Schottky contacts with high Schottky barrier height (SBH), low leakage current, and good thermal stability at high power performance. In order to increase the SBH and reduce the reverse leakage current, several kinds of metals with a high work function (Pt, Ni, Pd, and Au) were widely used as gate electrodes. However, those metal films react with AlGaN forming metal gallides at an elevated temperature (>600°C) [5]. The interfacial reaction of the metal contact with AlGaN often led to the degradation of the Schottky characteristics. However, during the diamond deposition, the Schottky contacts must withstand not only high temperatures (>700°C) but also aggressive conditions (>95% hydrogen plasma). Therefore, various investigations using rare-earth metals, alloy, and multilayer systems have been carried out.

For example, the Ir-based contacts showed lower contact resistance and the fabricated HEMTs revealed improved transconductance, breakdown voltage, saturated drain-source currents, and better rf performance. The edge acuity of the Ir-based contacts also remains excellent for standard anneals at 850°C for 30 s [6]. Preliminary thermal stability tests of the Ir-based contacts at 300°C for 300 h showed no significant change in the contact resistance or morphology [6].

Moreover, $IrO_2$ has more excellent thermal stability at high temperature, and therefore, it is expected that it could be used as the gate electrode for an AlGaN/GaN HFET with large SBH and good thermal stability [7]. By comparison of output I-V characteristics of C-HEMTs with the both as deposited Ir and $IrO_2$ gates (after storage tests carried out at temperature of 450°C for 24 h), $IrO_2$ gate-based c-HEMT exhibited higher saturation currents which was explained by higher 2DEG concentration in the channel. The thermally $IrO_2$ layers are highly promising as the based HEMT gate electrodes, while they are able to withstand rapid thermal annealing (RTA) at temperatures 800÷850°C for 30 s [8]. Thus, such layers seem to be also capable to withstand the diamond CVD process.

In this article, we studied the influence of the diamond deposition process on the Schottky gate electrodes (i.e. Ir and $IrO_2$) and electrical characteristics of AlGaN/GaN c-HEMTs for further fabrication of all-in-diamond c-HEMT devices working at high-temperatures/high-powers [9].

## 2. EXPERIMENTAL PART

The AlGaN/GaN heterostructures for HEMT fabrication were grown by metal-organic chemical vapor-phase deposition (MOCVD) system on a silicon substrate. The thickness of the AlGaN barrier layer and the GaN buffer layer was 20 nm and 4 µm, respectively. The aluminum mole fraction of the AlGaN is nominally 0.25. The defined AlGaN/GaN heterostructure is encapsulated with a very thin (2nm) GaN layer. We have proposed a circular topology of HEMT (c-HEMT [10]) to rapidly evaluate the impact of used gate layers on the transport properties of these devices. The circular- or square-gate HEMTs are very attractive as sensing devices mainly for pressure sensors [11 and high-power devices with suppressed current collapse and gate-lag effect [12]. In our experiments, circular source/drain ohmic contacts were formed using Nb/Ti/Al/Au metallic system, alloyed at 850°C for 35 s [13]. Iridium electron beam evaporation and lift-off were carried out subsequently to form 15 nm thick ring gate contacts in the second step [14]. Beside iridium, the $IrO_2$ was also studied as Schottky gate electrodes. For this purpose, the Iridium ring gate contacts were annealed in $O_2$ ambient using RTA at 700°C or 800°C for 1÷5 min.

The diamond coating were deposited by focused microwave chemical vapour deposition system (MWCVD) [15] using selective area nucleation process [16]. In order to suppress the spontaneous nucleation [17], optimized deposition conditions were used: microwave power 2 kW, process pressure 40 mbar, gas mixture of 5% $CH_4$ and 1.5% $CO_2$ in $H_2$, deposition temperature 580÷610°C and total time 6 h [18]. In addition, for experiments on the thermal stability of the metal oxide gate electrode layer ($IrO_2$) the deposition temperature was varied from 600°C to 1100°C controlled by the MW power and pressure (up to 4 kW and 70 mbar, respectively). For a comparison, the c-HEMTs with Ir gate contacts were also exposed to linear antenna MWCVD system [19, 20] at deposition temperature 400°C. The other process parameters were as follows: microwave power 2x1700 W, pressure 0.1 mbar, gas mixture 2.5% $CH_4$ and 10% $CO_2$ in $H_2$, deposition time 15 h.

The samples were analyzed by optical microscopy, scanning electron microscopy (Tescan MIRA3 FEG-SEM) and Raman spectroscopy (Renishaw InVia Reflex Raman spectrometer with the excitation wavelength of 442 nm). Moreover, an HP 4145B semiconductor parameter analyzer was employed to measure the Schottky gate and dc transistors characteristics.

## 3. RESULTS AND DISCUSSION

**Fig. 1** shows the output characteristics of AlGaN/GaN c-HEMTs without and with diamond coating (approx. 400 nm in thickness) for Ir gate electrode with lengths varied from 40 up to 160 µm. Diamond films were grown by selective area deposition [16,18]. Concerning the influence of diamond CVD on the gate electrodes we observed followings: the c-HEMT transistors were still functional after the diamond deposition for 6 hours at 600°C. However, their output characteristics decreased (e.g. by 10÷15 mA at $V_{DS}$ = 8V). We attribute this to degradation and/or peeling off the iridium gate electrode from the substrate (see **Fig. 1c**). We have considered possible reasons of this effect. Iridium has high melting point (approx. 2450°C), thus high temperature even up to 1500°C cannot affect its properties. We propose that Ir can degrade at much lower temperatures due to its film character at low thickness (no more bulk material) and presence of hydrogen plasma. Similar dependence was observed for nickel thin film. Even though the high melting point of nickel (~1450 °C), the Ni is melting at significantly lower temperatures (700 °C, plasma annealing) due to thin metal layer [21, 22]. Thin metal layers can form also droplets due to de-wetting of metal atoms, their surface migration, and clustering. It is believed that two dominant mechanisms are responsible for the conversion of metal film into clusters when treated with hydrogen plasma. The first mechanism is that of plasma etching during which the hydrogen plasma etches the metal film from top to bottom, producing metal particles. The other mechanism is called plasma-enhanced coalescence, where the hydrogen plasma etching only provides the “cracking” of the metal film. It was found out that the dominant process at hydrogen rich microwave plasma treatment is not the plasma etching, but the plasma-enhanced coalescence mechanism [22].

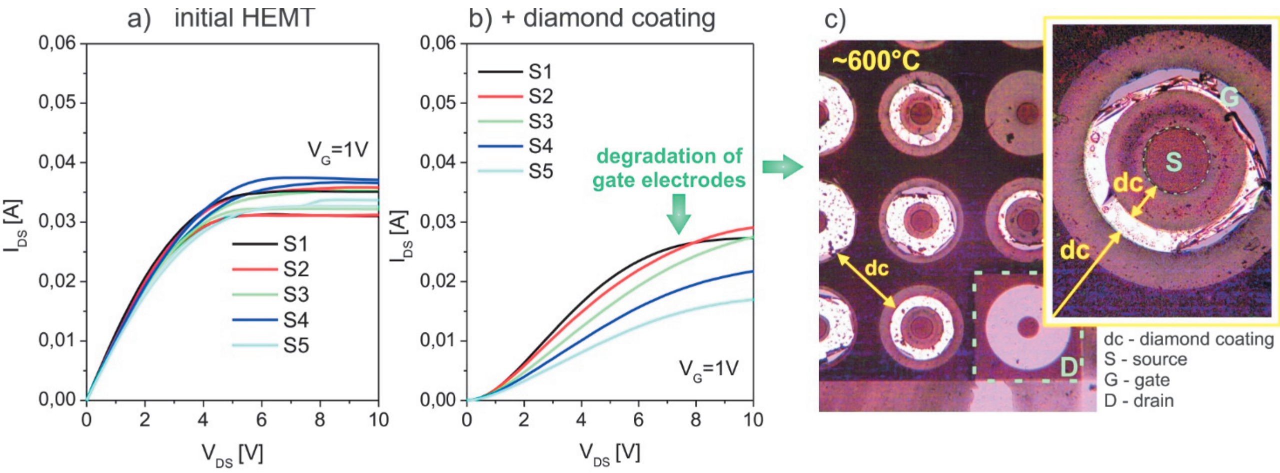


**Fig. 1** Output characteristics of AlGaN/GaN HEMTs without (a) and with (b) diamond coating (Note: labels S1-S5 correspond to different gate lengths; i.e. S1: Lg = 160 µm, S2: Lg = 140 µm, S3: Lg = 100 µm, S4: Lg = 60 µm, S5: Lg = 40 µm). **Fig. 1**c) shows the top-view optical images of c-HEMTs after diamond deposition in focused MW plasma at different magnifications (the whole diameter of one circular-HEMT structure is 480 µm)

In our case, more dominant is the thermally induced stress during the heating up to deposition temperature and cooling down to room temperature which lead to bending of the substrate due to different thermal expansion coefficient of materials (Si, GaN and diamond) [4,23]. This bending of the substrate with combination of low adhesion of thin metal layer could result in peeling off the Ir gate electrodes. The effect is proportional, i.e. higher the deposition temperature will results in higher thermally-induced stress (i.e. bending of the substrate). Therefore, we also investigated the influence of diamond deposition on the c-HEMTs gate electrode for low deposition temperatures (~400°C). Diamond films were grown by linear antenna plasma MWCVD system. Due to unique construction and plasma characteristics [19] this deposition systems allows diamond growth at temperatures as low as 250°C [24, 25]. However, its disadvantage for covering of AlGaN/GaN HEMTs by thick diamond layer (>2÷5 µm) lies in the very low growth rates (~5÷50 nm/h, [24]).

Nevertheless, it was found out that even at low deposition temperature of 400°C the Ir gate contacts revealed changes - bubble-like clusters were formed on the gate area (see **Fig. 2** white/yellow ring). Moreover, these changes affect also the c-HEMTs electrical properties.

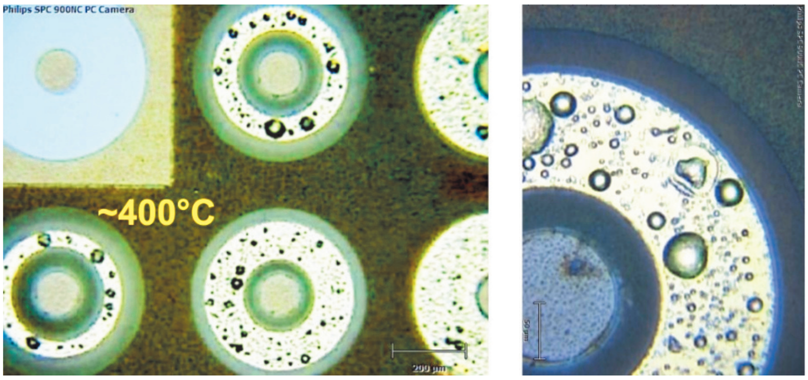


**Fig. 2** Optical images of c-HEMTs after diamond deposition in linear antenna MW plasma at different magnifications (the whole diameter of one circular-HEMT structure is 480 µm)

Due to application of Ir as gate electrodes was not successful, further we focused on the study of $IrO_2$. $IrO_2$ based Schottky gate electrodes were formed by rapid thermal annealing of Ir at 700÷800°C for 2÷5 min. After diamond deposition at 700°C for 4 hours the $IrO_2$ gate contacts revealed unchanged/undamaged morphology (**Fig. 3a**). By increasing of deposition temperature to (>900°C) the electrical properties of gate electrodes are getting worse probably due to the diffusion of hydrogen atoms into GaN layer. Nevertheless, for 1000°C no visible degradation or delamination of $IrO_2$ from the substrates was observed. We suppose that the degradation of c-HEMTs is related to damage the 2DEG by diffusion of hydrogen atoms deep into the semiconductor bulk during deposition process [26]. Similar effect was observed on Pt/NiO ring gate based Schottky diode hydrogen sensors [27], where the transient characteristics of the sensors showed a longer response time due to a longer diffusion path for hydrogen. Additional analysis by SIMS and XPS to confirm our considerations are under progress.

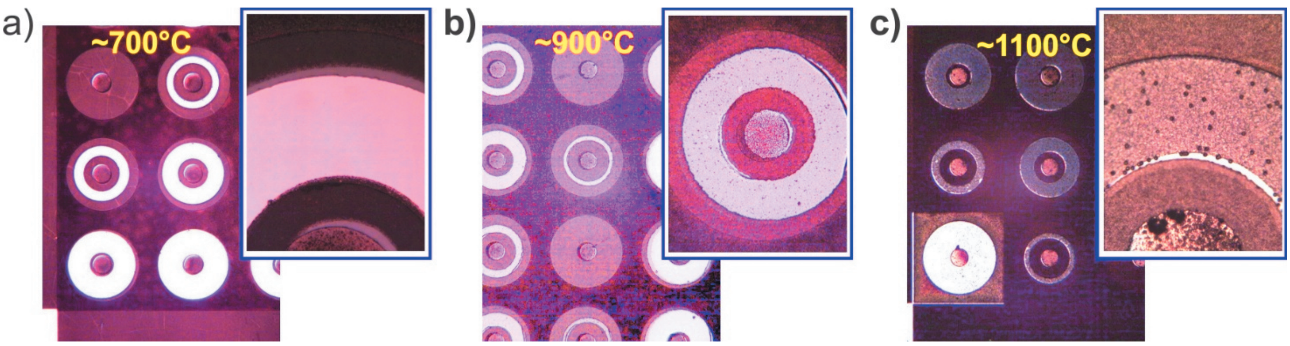


**Fig. 3** Optical images of c-HEMTs with metal oxide Schottky gate electrodes after diamond growth in focused MW plasma deposited at different temperatures. (Inset figures show detailed view of the transistor. The whole diameter of one circular-HEMT structure is 480 µm)

## 4. CONCLUSION

Diamond films were selectively deposited on AlGaN/GaN circular high electron mobility transistors by focused (ellipsoidal cavity reactor) and linear antenna (surface wave) microwave plasma at different temperatures varied from 400°C to 1100°C. Different effect of diamond deposition process on the degradation of the Ir or $IrO_2$ Schottky gate electrodes and on the electrical characteristics of transistors was found. Compared to c-HEMTS without diamond, the diamond-coated c-HEMTs exhibited degradation of Ir electrodes and change of transistors characteristics due to diamond CVD process. Even low temperature (400°C) was employed, still a visible deformation of Ir gate electrodes was observed. In contrast to this, the $IrO_2$ electrodes withstand the diamond deposition conditions for much higher temperatures (700÷900°C). For 1100°C, electrical properties degraded while no significant change of $IrO_2$ Schottky gate electrodes was observed. We suppose that the degradation of c-HEMTs is related to damage the 2DEG by diffusion of hydrogen atoms deep into the semiconductor bulk during deposition process. Based on our observations we propose that $IrO_2$ are good candidates for fabrication of thermally stable and high SBH gate contacts. Further outlooks are fabrication of all-in-diamond c-HEMT devices for high-power applications.

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