Optimization of Iridium RF-Sputter Process for AlGaN/GaN-based HEMT Gate Technology

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Abstract

Sputtered iridium films are the key element of FBH´s unique Schottky metal gate technology for AlGaN/GaN HEMT devices. Due to the piezoelectric properties of the AlGaN/GaN system, the metal deposition in the gate trench needs to be conformal and of low mechanical stress. In this paper we give a detailed insight into the sputtering parameters used for the deposition of the iridium gate metal and analyze the influencing factors like the working gas pressure, target-to-substrate distance, and static vs. rotating sputter mode on thin-film properties such as stress and electrical resistivity.

I. INTRODUCTION

Due to its outstanding properties, iridium is an excellent candidate for dense barrier coatings and is used for gas sensors and DRAM applications as well as catalyst material coatings [1,2]. For the application in GaN-based HEMT technology, iridium is of high interest because of its large work function of ~ 5.67 eV, which is comparable to that of platinum with 5.64 eV [3]. For platinum, however, there is significant evidence that carbon diffuses into it very quickly and corrupts its use as a diffusion barrier [1]. Iridium has the advantage that it shows only low solubility for carbon and acts as a much more stable diffusion barrier [1], which promotes device reliability of GaN HEMTs [6]. Fig. 1 shows a schematic of an AlGaN/GaN HEMT gate module using sputtered iridium metal. Typical gate lengths are in the range of 150 nm to 250 nm.

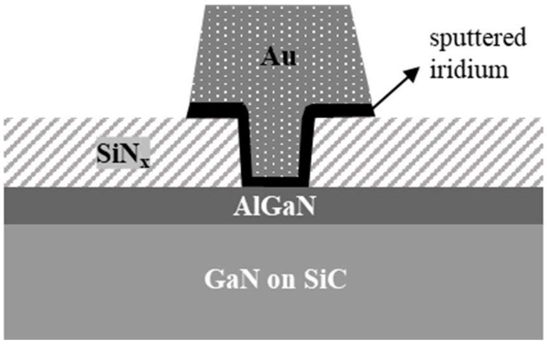

Fig. 1: Schematic cross section of the AlGaN/GaN HEMT gate with sputtered iridium Schottky barrier

The lattice mismatch between AlGaN and GaN causes tensile stress in the epitaxially grown AlGaN layer. Due to spontaneous and piezoelectric polarization in the epitaxial layer stack, a 2-dimensional electron gas (2DEG) forms near the AlGaN/GaN interface. It has been shown that the density of the 2DEG is sensitive to external stress [4,5]. Thus, any external stress either from the silicon nitride (SiN_x) passivation layer or from the gate metal itself affects the 2DEG density and has an impact on threshold voltage and other transistor properties. From a large number of publications on thin-film deposition it is well known that sputtering parameters like working gas pressure, substrate temperature, apparatus configuration and atom arrival direction, as well as the incorporation of impurities during the sputter process, affect the crystalline structure of the deposited film and its properties in terms of film stress, resistivity, and density [7,8].

In GaN HEMT fabrication, the control of the mechanical stress of the sputter-deposited iridium film is mandatory. Previously, we examined the impact of stress on transistor parameters and presented a detailed description of the fabrication flow [4-6]. In this paper we analyze the influence of iridium sputter parameters for the deposition on thin-film properties like film stress and electrical resistivity and provide insight into the optimization process to obtain dense, low-stress iridium sputtered films that act as effective Schottky barriers in 250 nm AlGaN/GaN HEMT devices.

II. EXPERIMENTAL

The deposition of the thin films was performed on a Leybold Z590 sputter tool. The chamber was evacuated at all times to a base pressure of 5E-4 Pa in order to prevent contamination of the deposited films with moisture or oxygen. Using a 13.56 MHz RF-source, an argon-based plasma was used with 0.88 W/cm² (200 W) power. The pressure control was done upstream, so the argon flow was varied for the experiments depending on the targeted working gas pressure (from 1.2 Pa to 6 Pa). The samples are transferred from a load lock into the chamber by a transfer robot. There are two process modes under investigation: a) a static sputtering process and b) a rotating process. In the rotating case, the substrate holder, which can load up to 6 substrates, rotates at

3 rpm. For the shown processes, a 0.88 W/cm² power density is used. The substrate holder is at a floating potential.

In case of the presented bias supported deposition (section III.E) the substrate is additionally biased at a potential of -100 V aiming at additional ion bombardment. All depositions have been performed on a 100 mm p-doped silicon <100> wafer and on a quartz glass substrate at room temperature. The wafers were analyzed by x-ray fluorescence to determine the iridium thickness using a Fischerscope® xdVμ. Using a KLA Tencor P17 surface profiler, the wafer bow was measured and the iridium film stress was determined according to the Stoney equation [9]. The electrical resistivity was analyzed using a Veeco AP-150 automatic four-point-probe measurement tool. For SEM cross sections, the samples were cleaved and analyzed using a Hitachi S-4800 field emission scanning electron microscope.

III. RESULTS AND DISCUSSIONS

A. Film Stress and Electrical Resistivity

For a fixed wafer-to-target distance of 100 mm and a sputtering power of 200 W, a variation of the working gas pressure was done. Fig. 2 shows the results for static sputtering processes in terms of film stress and electrical resistivity. A strong dependency of the derived film stress on the working gas pressure can be seen. At low pressure (1 Pa-2.8 Pa), the stress is compressive. Between 2.8 Pa and 3.0 Pa, the film stress is rather neutral. Increasing the working gas pressure leads to a tensile stress, which reaches a maximum of 1.47 GPa at 3.4 Pa pressure. It slowly decreases when the pressure is further increased.

However, the electrical resistivity follows a different trend. It exhibits a nearly constant value at a low level when the films are compressive. In the transition region, where the stress changes from compressive to neutral and tensile, the electrical resistivity increases. With a further increased working gas pressure, a saturation of the electrical resistivity is not seen within the investigated pressure range.

The behavior of the film stress with respect to pressure is in accordance with previous publications [8]. At low pressure, the sputtering atoms exhibit a high energy since interactions with other atoms are less likely as compared to higher pressures. The high energy of the atoms (neutral argon atoms as well as sputtered iridium atoms) results in a dense film since peening mechanisms take place in that growth regime. According to Thornton´s zone model [7], the growth can be attributed to Zone 2, resulting in columnar, dense grains. The low resistance values observed in the low-pressure range also indicate a dense film. In the range of compressive film stress, the resistance shows minimal values. With increasing pressure during growth, more particles can recombine resulting in neutral films. In this growth mode, densely packed fibrous growth is dominant [7]. The changing morphology is obviously reflected by the behavior of the electrical resistance. With the transition into another growth mode, an increase in resistance becomes apparent.

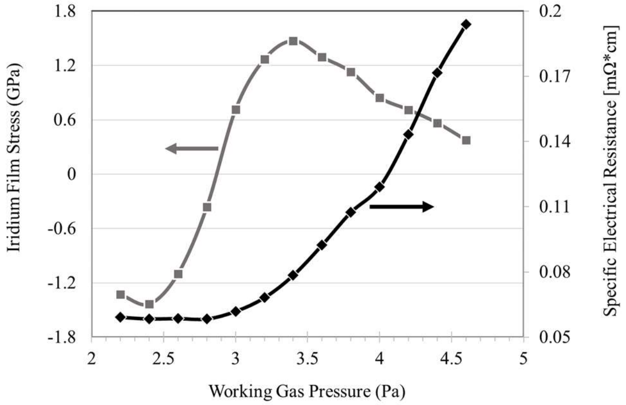

Fig. 2: Iridium film stress and specific electrical resistance depending on the inert working gas pressure (static mode, fixed wafer-to-target distance of 100 mm)

A further increase of the working gas pressure leads to more recombination and further lowers the kinetic energy of the involved particles. As a result, the grain growth is now expected to be more porous and less dense. The further increase of the electrical resistivity supports this assumption.

What are the criteria for the selection of the process window for iridium sputter deposition and what can we conclude from the data presented? First, the application as an efficient gate barrier demands a dense film. This can be found in the compressive growth regime. Secondly, the conductivity of the iridium film used should be as high as possible to establish a good gate contact. This criterion also applies to the compressively stressed area, while the conductivity hardly changes in this window. Thirdly, a shift in the electrical properties of the AlGaN/GaN 2DEG due to the inverse piezoelectric effect needs to be prevented. Therefore, the film should have as little internal stress as possible.

Based on these three criteria, we conclude that a slightly compressively strained iridium film should be targeted. In the presented work, this is the case at 2.8 Pa with -364 MPa compressive strain.

B. The Effect of the Sputter Distance

A further important parameter in magnetron-based sputtering is the target-to-substrate distance. It influences the homogeneity of the deposition, which is important for the device yield. On the one hand, a short distance leads to a higher thermal budget on the samples. On the other hand, a short distance increases the angular range of the atoms building up the thin film resulting in better conformity.

Fig. 3 shows the change of the pressure dependent stress when varying the target-to-substrate distance. For the used tool, 60 mm is the minimum and 120 mm is the maximum possible distance. From Fig. 3, two main findings can be made: Firstly, varying the distance will shift the process window to different pressure ranges. The shorter the distance, the more pressure is required for the same film stress value.

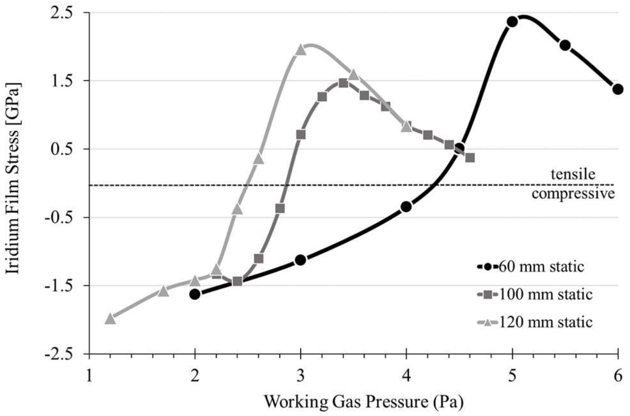

Fig. 3: Shift of the process window depending on the target-to-substrate distance (static mode).

The resulting stress depends on the kinetic energy of the particles, and thus, also on the number of elastic collisions that the atoms undergo while releasing energy. The number of collisions in a defined volume can be derived from the mean free path. In a low-pressure region, the mean free path is high and the particles perform a comparably small number of collisions at a fixed target-to-substrate distance. Vice versa, if the pressure increases, the number of recombination events increases. In order to achieve the same number of atom collisions on the path from the target to the substrate, the inert gas pressure must be adjusted if the target-to-substrate distance changes. In low pressure ranges, the optimal distance is larger as compared to higher pressure where due to the decreased mean free path length the optimal pressure range is shifted to higher values.

Both optimal process windows – low pressure at large distance and higher pressure at low distance – cause a similar number of collision events of the atoms on their path from the target to the substrate and thus result in similar kinetic energies that determine the film stress.

Moreover, it can also be seen from Fig. 3 that the process window for a defined film stress in the slightly compressive range is very narrow. Small deviations in the pressure result in large changes in the film stress. The data also suggests that the process response is less steep for the small target-to-substrate distance of 60 mm. This would have advantages for the controllability and stability of the process.

A further criterion to choose the right sputter distance is the non-uniformity. At low target-to-substrate distance, a bimodal distribution originating from the magnetron sputtering process was observed. The thickness non-uniformity at 60 mm target-to-substrate distance was 6.8% measured by x-ray-fluorescence on a 100 mm silicon wafer. At 100 mm distance the non-uniformity has a minimum of 4.8%. Further increasing the distance increased the non-uniformity slightly to 5.0%. Since a shorter distance also entails a larger angle of capture of the atoms, a target-to-substrate distance of 100 mm was found to be optimum.

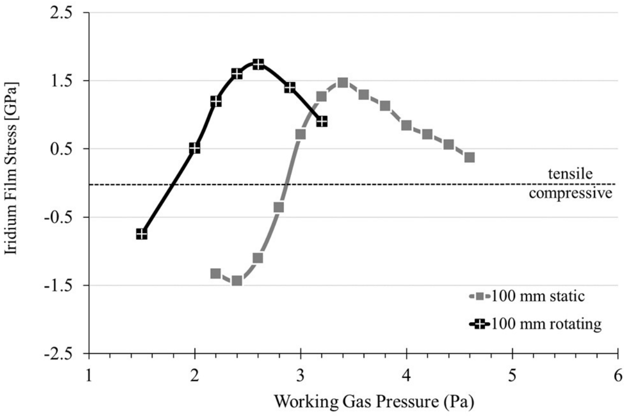

Fig. 4: Comparison of a static vs. rotation process mode depending on the working gas pressure.

C. *The Effect of the Sputter Mode (Static vs. Rotating)*

Whether the process is static or rotating has a fundamental influence on the wafer throughput. Since the overhead time for transferring wafers in the chamber is dominant, from a throughput perspective a rotating batch process would be preferred. In the Leybold Z590 sputter tool used, up to 6 substrates can be loaded into the chamber. The 6 substrates are positioned on a table that moves at 3 rpm. Since the target position is fixed, the wafers pass the target approximately every 20 seconds. For the static process, the deposition rate is 22 nm/min, for the rotating process the deposition rate is reduced to 6.3 nm/min.

Fig. 4 compares two processes with identical target-to-substrate distance of 100 mm. The process mode has a clear influence on the process window. The working gas pressure to obtain slightly compressive strain is shifted from 2.8 Pa in static mode to about 1.7 Pa in rotating mode. The following reasons may be responsible for that finding. A different thermal budget could be responsible since the deposition is not continuous in the rotating case. However, we do not assume a major impact since the growth condition is not in a range where thermally activated processes should play a role.

Another reason could be a change in structure of the layer since growth is periodically interrupted. Also, the incorporation of impurities could be responsible for the change in stress. Previous studies indicated that remaining moisture or impurities like hydrogen or oxygen have influence on the film stress [10]. Since iridium is known to getter oxygen [1], the formation of Ir-O species would have the potential to change the film stress. Due to the rotation, the film formation takes significantly longer, and in addition the wafers are not continuously in the plasma. For a large part of the deposition time, the layers are exposed to the residual gas atmosphere and thus have the opportunity to getter residual gas species. Although this hypothesis could not yet be supported, the risk of having oxide incorporation cannot be neglected. Therefore, it is recommended to run the process in static mode even if wafer throughput is impaired.

D. *Deposition of Iridium Films into Gate Trenches*

The proposed conditions to produce dense, slightly compressively strained and well-conducting iridium films are a working gas pressure of 2.8 Pa at a distance of 100 mm with a static magnetron sputter process. Fig. 5 shows a sputtered iridium film in an etched gate trench with 250 nm gate length. Although the angle of the etched gate is very steep (here: 87°), the film is continuous, smooth, and without any voids. The sputtered iridium film exhibits a good conformality (top to bottom) of 0.55 and a conformality (top to side) of 0.46.

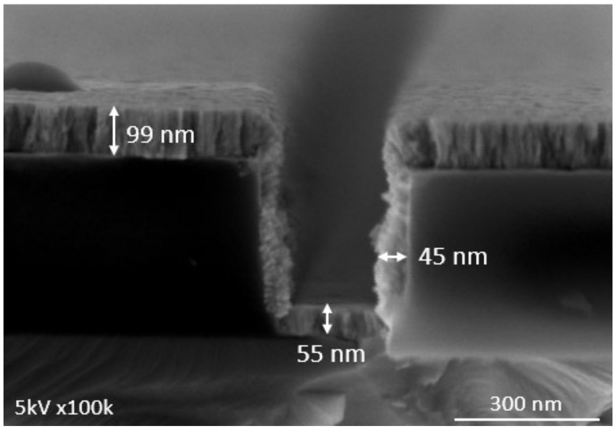

Fig. 5: SEM cross section of gate trench with sputtered iridium barrier.

E. *Further Optimization of Step Coverage*

Although the current process conditions show a good filling behavior, a further increase in step coverage of the iridium film was targeted. An additional substrate bias of -100 V was applied to achieve the desired sputtering effect on the substrate during the film growth. Fig. 6 shows the resulting gate structure. Due to the additional atom bombardment in the direction of the surface, the layer thickness decreased by ~ 25% on top of the structures. Although the top to bottom conformality remains constant at 0.54, the top to side conformality has increased to 0.67. The crystalline structure is as dense and columnar as in the standard sputter process. Since the substrate bias might have negative impact on substrate damage, that approach is under investigation.

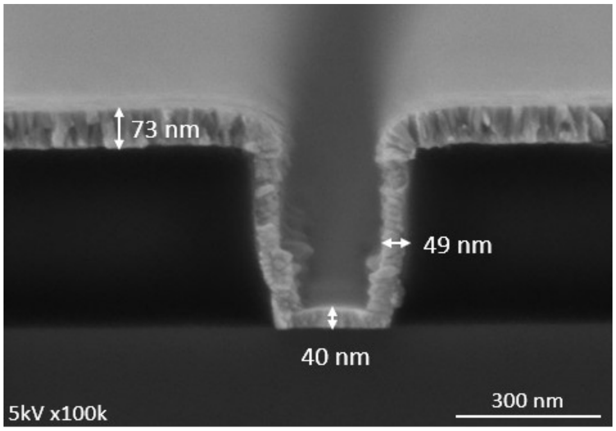

Fig. 6: SEM cross section of gate trench with sputtered iridium barrier deposited with superimposed bias voltage to optimize the filling behavior.

IV. CONCLUSIONS

The magnetron sputtering process of thin iridium films has been investigated under various process conditions. It was shown that dense iridium films exhibiting low electrical resistivity, which are prerequisite for an efficient gate contact, show slight compressive stress. Under the process conditions applied in the present study, at a working gas pressure of 2.8 Pa a compressive strain of the iridium film of -364 MPa was found to be a good working point. However, the process window shifts towards lower or higher pressure ranges as the target-to-substrate distance is changed. Furthermore, the stress values obtained depend on whether the substrates were kept static or were rotated during film deposition. Since an influence of gettered oxygen cannot be excluded for the rotating process, static sputtering is proposed. Smooth and continuous filling of the gate trench is demonstrated. The sputtering with superimposed bias voltage shows an improved filling behavior and should be investigated further.

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