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The Role of Selective Pattern Etching to Improve the Ohmic Contact Resistance and Device Performance of AlGaN/GaN HEMTs

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ABSTRACT

In this work, we report the processing and DC performance of fabricated AlGaN/GaN HEMT devices using 3 different patterned Ohmic contact structures. The types of Ohmic contact patterns used are horizontal, vertical and chess. A device with a conventional Ohmic contact was also fabricated for comparison. Two different etch depths were investigated, a ~ 9 nm and ~ 30 nm for a shallow and deep Ohmic recess etching, respectively. The lowest contact resistance of 0.32 Ω.mm was observed for a deep horizontal patterned structure. The fabricated device with this structure also demonstrated the highest maximum saturation drain current of 1285 mA/mm and maximum transconductance of 296 mS/mm compared to other devices. The horizontal patterned structure utilizes the uneven AlGaN layer thickness underneath the Ohmic metal contacts. The formation of sidewall areas on AlGaN surface during the patterned etching process provides better contact of Ohmic metal resulting in more tunnelling current between the Ohmic metal and AlGaN barrier thus reducing the contact resistance. This approach also provides the lowest contact resistance due to removal of AlGaN barrier layer (patterned etching) and it is in parallel with the lateral current of the 2DEG resulting in better tunnelling current compared to the vertical and chess patterned structures. The contact resistance can be further improved by optimization the etching depth prior to Ohmic metal deposition. The results indicate the potential of the Ohmic patterned etching structure to further improving the performance of GaN devices.

Keywords: AlGaN/GaN, etching high electron mobility transistors (HEMTs), Ohmic contact.

1. INTRODUCTION

AlGaN/GaN high electron mobility transistors (HEMTs) are very promising for high-power, high-frequency and RF electronic applications due to their exceptional material properties, such as wide bandgap of 3.4 eV, high electron mobility >1800 cm^2/V.s, high saturation velocity and high breakdown field 3.3 MV/cm [1][2][3]. Reducing the Ohmic contact resistance is crucial to fully utilize the benefits of GaN heterostructure devices. The recessed Ohmic contacts i.e the removal of AlGaN barrier layer prior to Ohmic metal deposition is a common way to improve the performance of Ohmic contacts on AlGaN/GaN HEMTs [4][5]. Several methods have been also reported to reduce the contact resistance of AlGaN/GaN heterostructure such as the usage of different metal stacks for Ohmic contacts [6][7], regrown of n+ GaN on Ohmic regions [8][9], and surface plasma treatments prior to Ohmic metal deposition [10][11]. Recently a few works on the etching pattern structures in Ohmic contacts have been reported and gave further reduction of contact resistance to AlGaN/GaN heterostructures [12][13]. The concept used the uneven thickness of AlGaN barrier underneath the Ohmic metal contacts [14]. There is an additional step for the fabrication process where the Ohmic contact regions are etched first prior to Ohmic metal deposition. The etching depth also plays an important role to reduce the Ohmic contact resistances [14].

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In this paper, we processed and characterized three (3) different patterned Ohmic contact structures (chess, vertical and horizontal) employing both shallow (~ 9 nm of etch depth) and deep (~ 30 nm of etch depth) Ohmic recess etching using the transfer length method (TLM). The conventional or planar Ohmic contact structure was also fabricated for comparison. GaN devices were also processed and characterized to evaluate their performance. The organization of the paper is as follows: Section 2 describes the patterned TLM structures and device fabrication, Section 3 deals with results and discussions, while concluding remarks are given in Section 4.

2. PATTERNED TLMs AND DEVICE FABRICATION

The epitaxial layer structure used in this work was grown by Cambridge University, UK, using metal-organic chemical vapour deposition (MOCVD) on a 1-mm thick high-resistivity (HR) silicon substrate. The wafer structure consists of (from top to bottom), a 2-nm GaN cap layer, 21-nm $Al_{0.25}GaN$ barrier layer, 1-nm AlN inclusion layer, 200-nm GaN channel layer, 850-nm GaN and 1.7-µm AlGaN buffer layers, and 250-nm AlN nucleation layer. Two samples were prepared and processed for Ohmic recess etching. The first sample was used for shallow etching (etch depth of 9 nm) above the 2DEG channel, and the second sample was used for deep etching (etch depth of 30 nm) below the 2DEG channel. Both samples have the conventional or planar (no pattern) and different TLM pattern structures (chess, vertical and horizontal) as shown in Figure 1. The device structure corresponding to each of these different TLM patterns was also included to evaluate the device performance. The wrap-around gate design (where the gate encircles the drain contact) structure was used for device evaluation. The cross-section schematic illustration of the fabricated AlGaN/GaN HEMT devices with a shallow and deep Ohmic recess etching are shown in Figures 2a and 2b, respectively.

The fabrication starts with the mesa isolation using the Cl_2/Ar gases and the etched depth of 260 nm was measured. For the TLM pattern structure, the etching was done using inductively coupled plasma (ICP) 180 tool with the following recipes: chamber pressure of 20 mTorr, mixture of BCl_3 and Cl_2 gases with flow rates of 5/10 sccm, and ICP and RF power of 100 and 13 watts respectively. The two etching depths of ~ 9 nm and ~ 30 nm were compared for shallow and deep Ohmic recess etching, respectively. Prior to Ohmic metal deposition, an in-situ argon (Ar) etch for 30 seconds was applied to remove native oxide on the sample surface. Metal stacks of Ti/Al/Ni/Au (30/180/40/100 nm) was deposited using E-beam evaporator, followed by a rapid thermal annealing (RTA) at 800°C for 30 seconds in N_2 environment. Finally, Schottky metal stack of Ni/Au (20/200 nm) was deposited for the gate contact. The fabrication was done by a combination of photolithography and electron beam lithography (E- beam) processing. E-beam lithography was used to get precise sizes of the TLM pattern structures which consist of the smallest pattern size of 2 µm as shown in Figures 1b, 1c and 1d. The width of the TLM structure is 150 µm with the gap spacings, L, of 5, 7, 9, 11 and 13 µm. The device dimensions used are as follows: gate width (W_G) of 60 µm, gate length (L_G) of 3 µm, drain to source distance (L_{DS}) of 12 µm, gate to drain (L_{GD}) of 5 µm and gate to source (L_{GS}) of 4 µm.

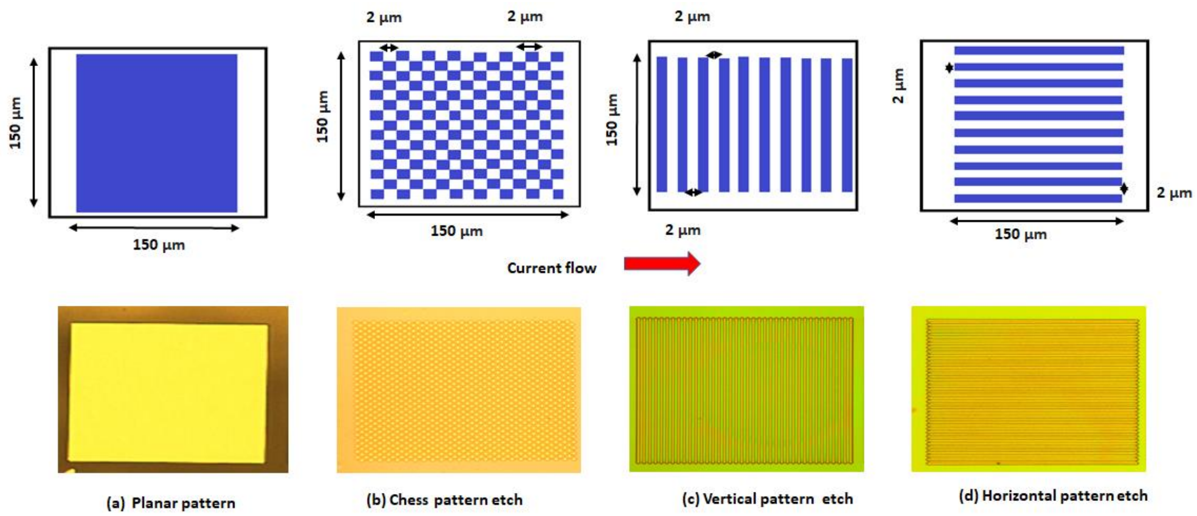

Figure 1. Top-view illustrations of the patterned surface of Ohmic contact using (a) conventional or planar (b) chess pattern etch (c) vertical pattern etch, and (d) horizontal pattern etch of AlGaN/GaN HEMT structures.

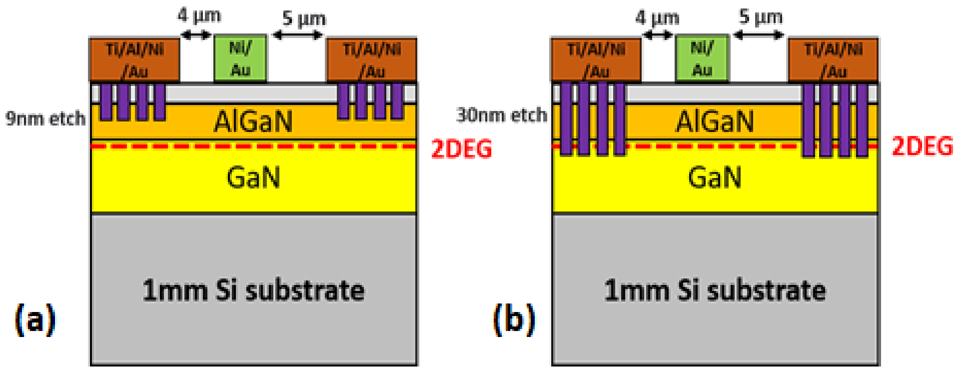

Figure 2. The cross-section schematic illustration of the fabricated AlGaN/GaN HEMT structures with (a) shallow (~ 9 nm of etch depth) (b) deep (~ 30 nm of etch depth) Ohmic recess etching.

3. RESULTS AND DISCUSSION

3.1 TLM measurements

Figure 3 shows the measured contact resistances, RC, of a shallow (~9 nm of etch depth) and deep (~ 30 nm of etch depth) Ohmic recess etching on 3 different TLM patterned structures along with the conventional TLM structure. The conventional or planar structure (no etching process is done) on both samples showed the same Ohmic contact resistance. The measured contacts resistances of TLM patterned structures show lower contact resistance both for shallow and deep Ohmic recess compared to the conventional TLM structure. This is due to the uneven AlGaN barrier layer thickness underneath the Ohmic metal contacts. The cross-section schematic illustration of TLM patterned etching structures for a shallow and deep Ohmic recess are shown in Figures 4a and 4b, respectively. The formation of sidewall area on AlGaN surface during the patterned etching process provides better contact of Ohmic metal resulting in more tunnelling current between Ohmic metal and the AlGaN barrier thus, reducing the contact resistance [14].

As for the conventional TLM structure (see Figure 4c), the Ohmic metal sits on the even (planar) AlGaN layer without the sidewall area and no ohmic recess etching resulting in higher contact resistance. Further reduction of contact resistance for all 3 patterned etching structures was observed with a deep Ohmic recess (~ 30 nm of etch depth) due to the close contact between Ohmic metal and the 2DEG as shown in Figure 4b. The lowest contact resistance of 0.32 Ω.mm was observed for a deep horizontal patterned structure. These results are in good agreement with the obtained results from the previous published works in [12] where a deep ohmic recess etching (below the 2DEG) was performed prior to Ohmic metal deposition. The horizontal patterned structure provides the lowest contact resistance due to the removal of AlGaN barrier layer (patterned etching) and it is in parallel with the lateral current of the 2DEG (see Figure 1d) resulting in better tunnelling current compared to the vertical (see Figure 1c) and chess patterns (see Figure 1b) where the patterned etching is perpendicular to the lateral current of 2DEG resulting higher contact resistances. It was also observed that the measured contact resistance of chess patterned etching is higher than the conventional TLM structure for a shallow Ohmic recess. The reason for this is not clear and needs further investigation.

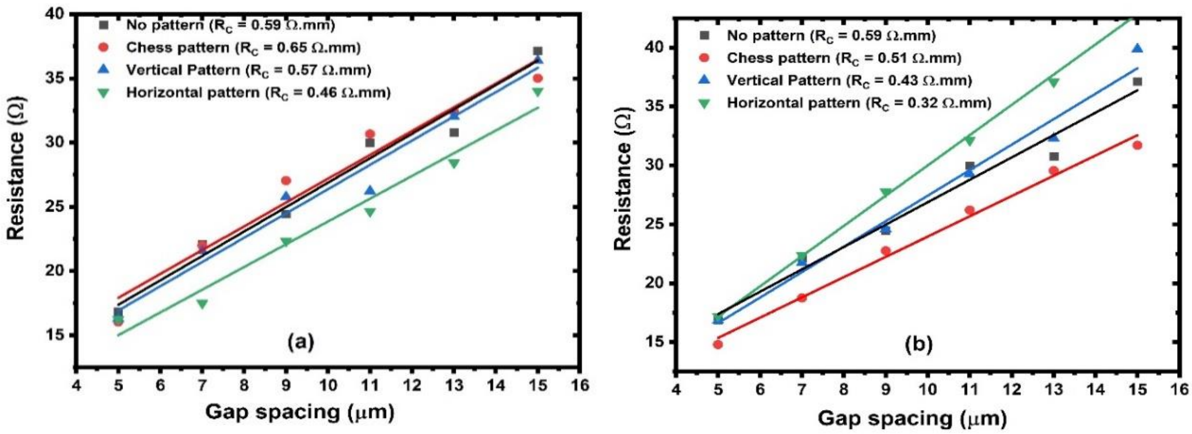

Figure 3. Measured contact resistances, RC, of (a) shallow and (b) deep Ohmic recess etching on 4 different TLM pattern structures.

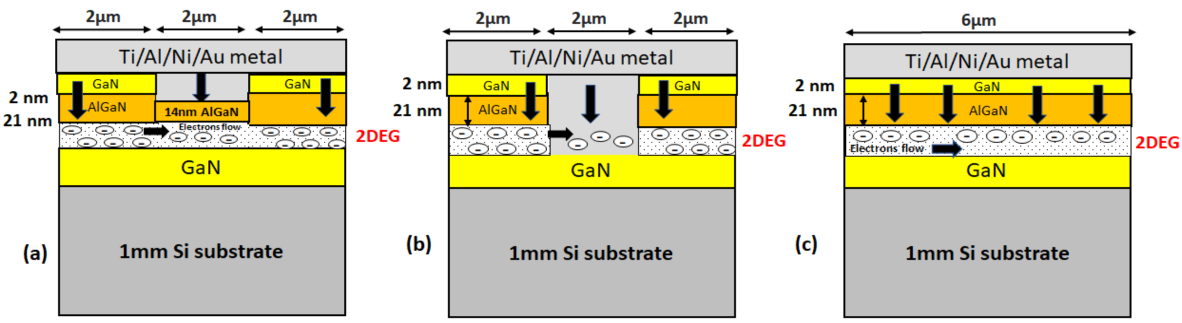

Figure 4. The cross-section schematic illustration of (a) shallow patterned etching (b) deep patterned etching (c) conventional or planar structure of Ohmic metal contact to AlGaN/GaN HEMT structures.

3.2 Device characterization

All fabricated devices were measured using the Keysight Agilent's B1500A semiconductor device analyser at room temperature. Figure 5 shows the measured output characteristics of the fabricated AlGaN/GaN HEMTs with a shallow (~ 9 nm etch depth) and deep (~ 30 nm etch depth) Ohmic recess etching of 3 different patterned Ohmic contacts and conventional or planar contact. The device with a conventional Ohmic contact on both samples exhibit a maximum saturation drain current of 970 mA/mm and 972 mA/mm. Note that there is no Ohmic recess etching for the device with a conventional Ohmic contact. As expected, the device with a horizontal patterned Ohmic contact shows higher maximum saturation drain current compared to other devices for both etching depths where the highest maximum saturation drain current of 1285 mA/mm was observed for a deep Ohmic recess. No obvious difference of maximum saturation drain current between devices with a vertical patterned and conventional Ohmic contacts while the devices with a chess patterned Ohmic contacts show lower maximum saturation drain current both for shallow and deep Ohmic recess. The same trend was observed for the measured maximum transconductance of the fabricated devices. These results are in agreement with the measured contact resistances as observed in Figure 3.

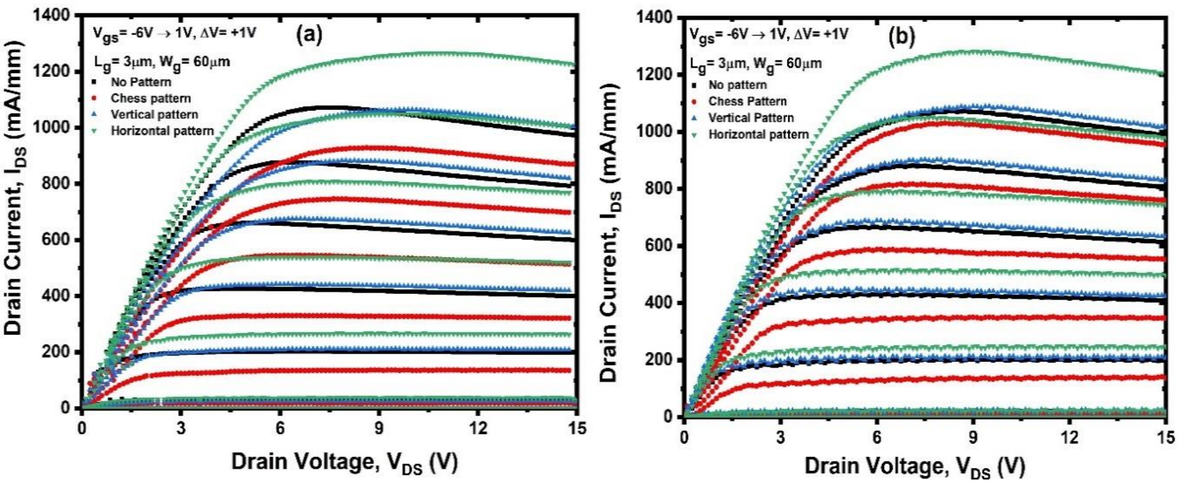

Figure 5. The measured output characteristics of the fabricated AlGaN/GaN HEMTs with a (a) shallow (b) deep patterned etching of 4 different TLM structure.

The transconductance characteristics of the fabricated AlGaN/GaN HEMTs measured at drain-to-source voltage, V_{ds} = 7 V are shown in Figure 6. The highest maximum transconductance was observed on the device with a horizontal patterned Ohmic contact which gives values of 284 mS/mm and 296 mS/mm for a shallow and deep Ohmic recess respectively. No obvious difference of maximum transconductance between devices with a vertical patterned Ohmic contact and conventional Ohmic contact structures while the device with a chess patterned Ohmic contact shows a lower maximum transconductance for both a shallow and deep Ohmic recess. The measured threshold voltage, V_{th} of - 4.1 V was observed and this value is consistent for all devices for a deep Ohmic recess. However, there is a shift toward the negative direction of the measured threshold voltage for devices with a horizontal and vertical patterned Ohmic contacts. This behaviour needs to be further investigated.

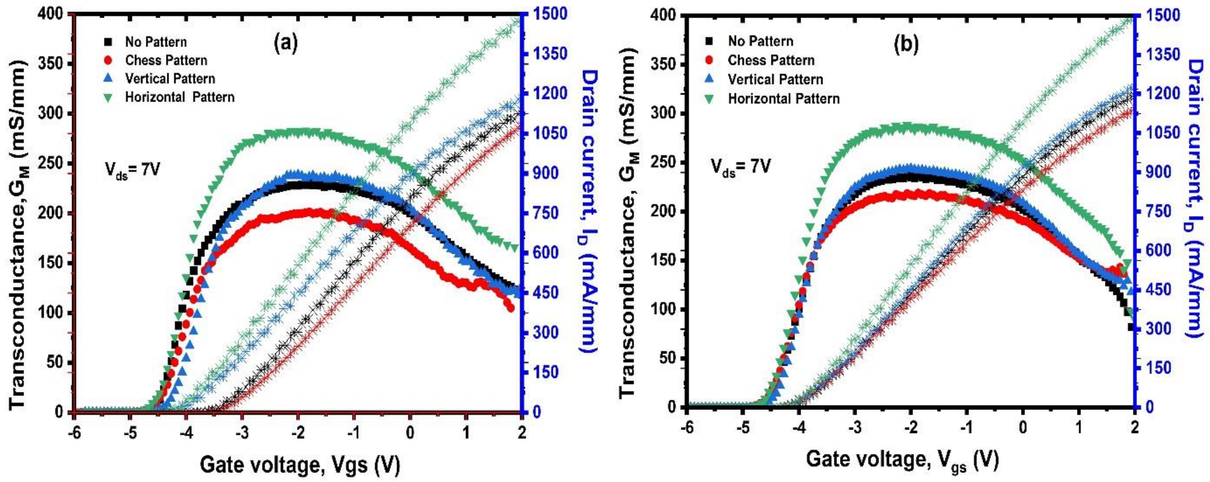

Figure 6. The measured transconductance of the fabricated AlGaN/GaN HEMTs with (a) shallow Ohmic recess etching (b) deep Ohmic recess etching with 4 different TLM pattern structures.

All devices exhibit lower gate leakage currents for a deep patterned Ohmic recess etch (compared to a shallow patterned Ohmic recess etch), where the lowest value is observed on the device with a horizontal patterned Ohmic contact as shown in Figure 7. These results corroborate the highest maximum saturation drain current and transconductance observed for this device. However, higher gate leakage currents were observed for devices with a shallow patterned Ohmic contacts compared to the device with a conventional Ohmic contact. The reason for this is not clear and needs further investigation.

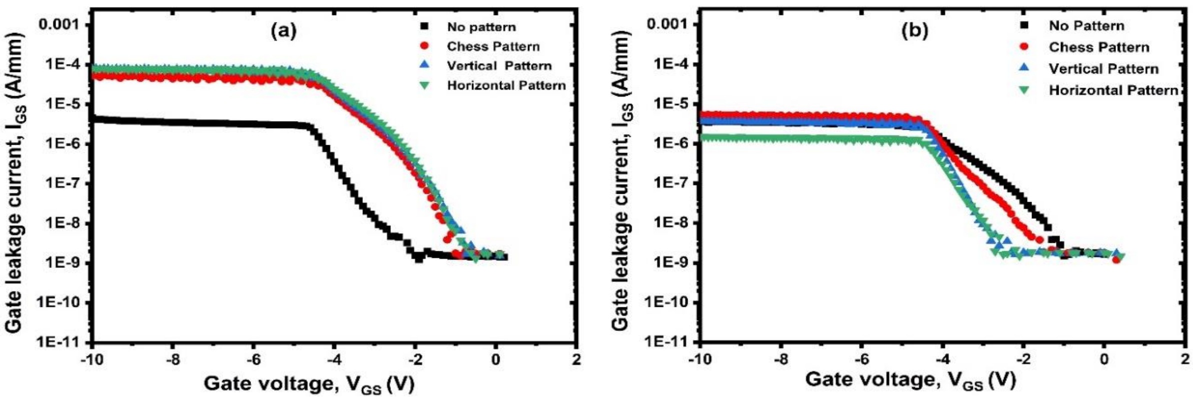

Figure 7. The gate leakage current characteristics of the fabricated AlGaN/GaN HEMTs with a (a) shallow Ohmic recess etching (b) deep Ohmic recess etching with 4 different TLM pattern structures.

4 CONCLUSION

We have successfully fabricated and measured AlGaN/GaN HEMT devices using 3 different patterned Ohmic contact structures. The types of Ohmic contact patterns used are horizontal, vertical and chess. A device with a conventional Ohmic contact was also fabricated for comparison. Two etching depths were used were ~ 9 nm and ~ 30 nm resulting trenches above and below the 2DEG channel respectively. The lowest contact resistance of 0.32 Ω.mm was observed for a deep horizontal patterned structure. The fabricated device with this structure also demonstrated the highest maximum saturation drain current of 1285 mA/mm, maximum transconductance of 296 mS/mm and gate leakage current of 1.5μA/mm which is better compared to other fabricated devices. We found that the uneven AlGaN layer thickness underneath the Ohmic metal contacts is responsible for reducing the Ohmic contact resistance. The formation of sidewall area on AlGaN surface during the patterned etching process provides better contact of Ohmic metal resulting in more tunnelling current between the Ohmic metal and AlGaN barrier thus reducing the contact resistance. We also found that the types of Ohmic patterned etching structure used and the Ohmic recess depth play a vital role in reducing the Ohmic contact resistance thus improving the device performance.

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