

## Van der Waals Epitaxy of GaN on Graphene by ECR-MBE

Van der Waals epitaxy, the crystal growth on two-dimensional (2D) layered materials, is one of the promising procedures to relax the lattice matching condition, which often limits the epitaxy of crystalline materials [1]. Fabrication of high-quality transferable crystals is a promising way to improve the performance of semiconductor optical devices [2, 3]. In addition, it is the effective route to integrate the 2D layered materials and conventional compound semiconductors [2]. Despite of these attractive features, there are a few studies demonstrating the synthesis of device-quality thin films of III–V nitride semiconductors on a graphene [2, 4, 5]. Especially, in the case of molecular beam epitaxy (MBE) growth, the control of nitrogen plasma damage is indispensable to avoid introducing dangling bonds which could be nucleation centers of misoriented crystals.

Here, we have demonstrated the effective MBE procedure, “Metal covered van der Waals epitaxy” to control the plasma damage and the number of nucleation centers using electron-cyclotron-resonance plasma-excited MBE (ECR-MBE) [6]. Usually, nitrogen plasma generated by ECR-MBE includes numerous nitrogen ions, including  $N^+$  and  $N_2$  which can react with carbon atoms on graphene and sputter them. In the proposed method, the Ga supply and short nitrogen-rich supply are repeated twenty times to obtain GaN films. Therefore, surface of graphene is always covered by Ga or GaN which could reduce the plasma damage on graphene surface.

Resulting in metal covered growth, we obtained the c-axis oriented GaN film with small grains on the graphene transferred onto  $SiO_2/Si$  substrate as shown in Fig. 1 (b). It was different from the growth of small misoriented crystals on graphene by usual ECR-MBE process as shown in Fig. 1 (a). In addition, the thin film with flat surface without small grains was obtained on the thick graphite as shown in Fig. 1 (c). The flatter surface of graphite without dangling bonds enables the realistic growth of GaN. We confirmed the strain of obtained crystals were relaxed.

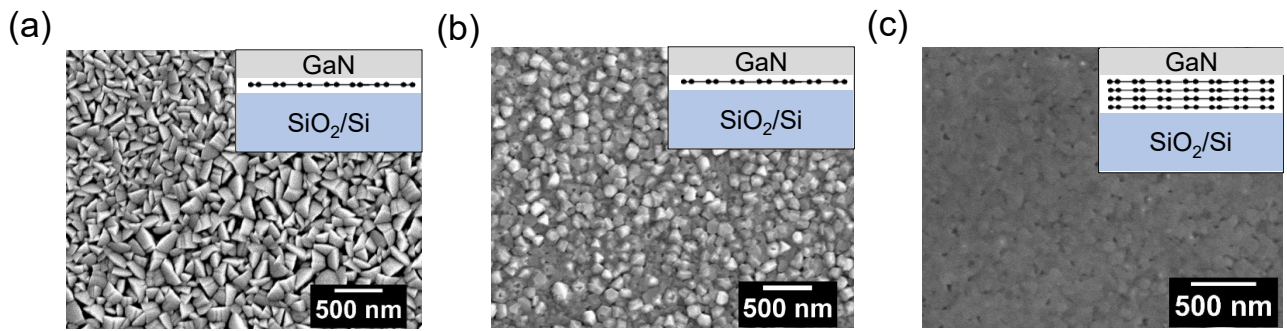
This approach was more effective on the graphene transferred onto a GaN template. The growth of small grains was suppressed and a well-coalesced GaN thin film was obtained as shown in Fig. 2. The EBSD signal suggests that this film is highly c-axis oriented. This result indicates the importance of supported substrates under the graphene layer on the van der Waals epitaxy. The electric potential of the GaN template was unscreened by graphene, which enables the quasi-homo-epitaxial growth of GaN on graphene. Such remote epitaxy was also reported in van der Waals epitaxy of GaAs [3]. This procedure would open a new path for the fabrication of 2D–3D structures for various device applications. Further studies on the optimization of cover supply process will be discussed in the presentation.

### References

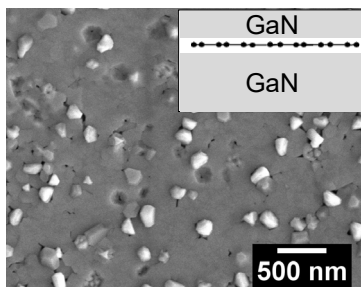
- [1] A. Koma, et. al., *Microelectron. Eng.* **2**, 129 (1984).
- [2] J. Kim et. al., *Nat. commun.* **5**, 4836 (2014).
- [3] Y. Kim et. al., *Nature* **544**, 7650 (2017).
- [4] J. W. Shon et. al., *Sic Rep.* **4**, 5325 (2014).
- [5] T. Araki et. al., *Appl. Phys. Exp.* **7**, 071001 (2014).
- [6] U. Ooe et. al., *Jpn. Jour. Appl. Phys.* in press (2019).

This work was supported by JSPS KAKENHI Grant Numbers JP16H03860, JP16H0615, 18H04294, 15H03559, Murata science foundation, Iketani science foundation.

## Figures



**Figure 1:** (a) SEM image of GaN crystals grown on graphene/SiO<sub>2</sub>/Si by ordinal MBE growth. (b) SEM image of GaN crystals grown on graphene/SiO<sub>2</sub>/Si by metal covered van der Walls epitaxy. (c) SEM image of GaN crystals grown on thick graphite by metal covered van der Walls epitaxy.



**Figure 2:** SEM image of GaN crystals grown on graphene/GaN template by metal covered van der Walls epitaxy