Neutral Beam Technology for Damage-free Etching Processes

Seiji Samukawa
Institute of Fluid Science, Advanced Institute for Materials Research and Material Solutions Center, Tohoku University
2-1-1 Katahira Aoba-ku Sendai, Miyagi, 980-8577, Japan, E-mail:samukawa@ifs.tohoku.ac.jp, TEL:+81-22-217-5240

Keywords: Neutral Beam Process, Plasma Induced damages, Defect-free, GaN HEMT, InGaN LED

Abstract

Advances in plasma process technology have contributed directly to advances in the miniaturization and integration of semiconductor devices. However, in semiconductor devices that encroach on the nanoscale domain, defects or damage can be caused by charged particles and ultraviolet rays emitted from the plasma, severely impairing the characteristics of nano-devices that have a larger surface than bulk areas. It is therefore essential to develop a method for suppressing or controlling charge accumulation and ultraviolet damage in plasma processing. The neutral beam process developed by the author is a method that suppresses the formation of defects at the atomic layer level in the processed surface, allowing ideal surface chemical reactions to take place at room temperature. This technique is indispensable to develop future innovative nano-devices. We are using this technique to develop future innovative nanodevices, such as high speed GaN HEMT and InGaN LED.

1. Introduction

In the fabrication of semiconductor devices, reactive plasmas are widely used in key processes such as microfabrication, surface modification and film deposition, and there are now demands for processing precision at the atomic layer level, and for deposition accuracy that allows the control of structures at the molecular level. However, in ultra-miniature nanoscale devices that will become the mainstream in the future, the use of plasma processes can cause serious problems such as abnormal etching and breakdown of insulation films by the accumulation of ions or electrons emitted from the plasma as shown in Fig. 1, also the formation of surface defects (dangling bond) of over a few tens nm in depth by exposure to ultraviolet (UV) emissions from the plasma.[1-4]

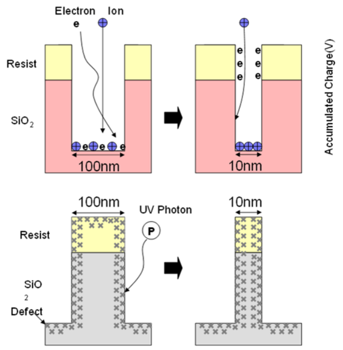


Fig. 1 Charging and UV photon irradiation Problems during plasma etching processes.

In particular, since nano-scale devices have a larger surface area compared with the bulk material, plasma processes can have a large influence on the electrical and optical properties of devices due to process-induced defects caused by ultraviolet exposure, which has not caused a problem in the presented devices of 32 nm. Furthermore, since future nanodevices will require size control of three-dimensional structures at the atomic layer level, it will be absolutely essential to control surface chemical reactions with high precision and selectivity at the atomic layer level. Neutral beam process technology has attracted attention as a way of solving these issues.[5,6], as shown in Fig. 2. The neutral beam suppresses the incidence of charged particles and UV photon radiation onto the substrate, and is able to expose the substrate only to energy controlled neutral beam (neutral beam motion energy can be precisely controlled by ion acceleration energy with the applied electric field before neutralization), resulting in ultra-precise nano-processing that can suppress the formation of defects at the atomic layer level and control surface chemical reactions with high precision.

This paper introduces the neutral beam application to atomic layer defect-free etching (ALE) for GaN devices that have recently been pursued.

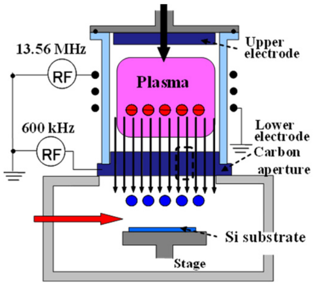


Fig. 2. Neutral beam generation device developed based on new concepts.

2. Effects of UV irradiation for Surface Reactions during Plasma Etching Process

We quantitatively investigated the effects of photon irradiation with a UV lamp during high-density Cl neutral beam etching process of Si.[7)] The goal was to understand the wavelength of photons for enhancement of surface reaction during the chlorine plasma Si etching process. We found that UV from 220 to 380 nm dramatically enhanced Si surface reactions with chlorine atom beam. This result suggests that the irradiation of UV photons enhance surface chemical reactions during the Cl_2 plasma etching processes.

The UV lamp was set at a position of 90 degree from the neutral beam source, as shown in Fig.3. We used a short-arc Xe flash lamp (pulse discharge) for irradiation of

UV photons to the Si sample surface. Figure 4 shows the spectra (from 200 nm to the visible region) irradiated from the lamp to the substrate surface. Higher photon intensity was observed in the UV region from 220 to 400 nm, than in the visible region. The power density of the irradiated photons was monitored by a calorimeter and fixed at 38 mW/cm^2. The photon irradiation frequency was fixed at 8Hz [pulse width of on-time was 25 ms in full width at half maximum (FWHM)]. Additionally, the UV photons of less than 380 nm could be cut using the UV photon filter to clarify the effects of UV photons and visible photons for the surface reactions. We investigated the effects of photon irradiation on etching depth as a function of RF bias power and the irradiated photon wavelength with and without the filter of the UV photon region from 220 to 380 nm, as shown in Fig. 5. By changing the radio-frequency (RF) bias power from 0 to 80W, the Cl beam energy could be controlled from 10 to measured using atomic force microscopy (AFM). Irradiation of UV photons (from 220 to 380 nm) dramatically increased etching depth under any RF bias conditions, whereas irradiation of visible photons did not increase etching depth at the same Cl beam condition. This result suggests that UV photon irradiation effectively enhanced the surface chemical etching reactions of Si with chlorine. The increase in the etching rate corresponds to increase in the defect density on Si surface. In summary, we are the first to find that UV from 220 to 380 nm dramatically enhances Cl reactions with Si. These results suggest that UV photon irradiation to the surface dramatically enhances surface reactions during the chlorine neutral beam Si etching processes. We consider this to be due to generating the crystal defects by UV irradiation on the Si surface. This means that UV irradiation plays a very important role in surface reaction even in the Cl_2 plasma etching processes. Namely, our developed neutral beam process is mainstream for atomic layer defect-free top-down process in sub-10 nm nano-fabrication in place of plasma processing.

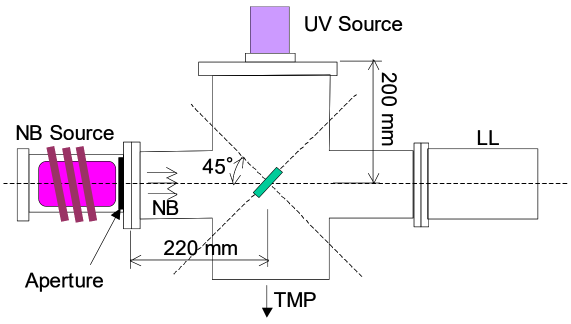


Figure 3 Illustration of experimental set-up by combination of our developed neutral beam source and UV lump.

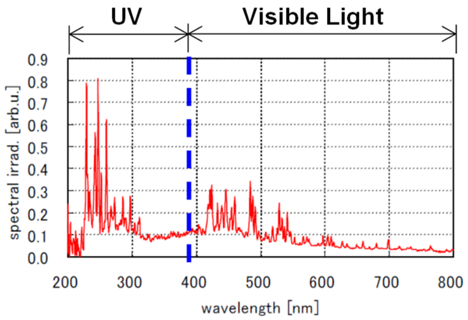


Figure 4. Photon spectra (from 200 to 800 nm) irradiated from a short-arc Xe flash lamp to substrate surface. The photon irradiation power density and photon irradiation pulse frequency ranged from 0 to 50mW/cm2 and from 0 to 8 Hz (on-time was fixed at 25 ms), respectively.

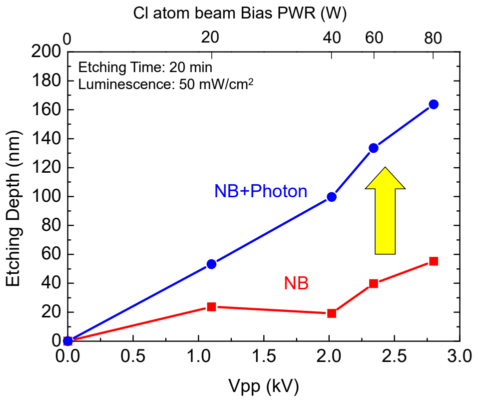


Figure 5. Effects of photon irradiation (power: 38mW/cm2, frequency:8 Hz) on etching depth as a function of RF bias power during Cl neutral beam etching process.

3. High Speed AlGaN/GaN HEMTs

We investigated a promising approach for the gate recess process with a suppressed current collapse in GaN-based high electron mobility transistors (HEMTs) by means of neutral beam etching.[8] A recessed gate structure has been widely studied as a way to realize normally-off operation in GaN, InP, and GaAs based HEMTs, as shown in Fig. 6. Since GaN-based materials are usually etched by plasma process, plasma-induced damage is a serious concern. NB is free from electrical charges and UV photons, resulting in an accurate control of etching depth and less plasma-induced damages. Fig. 7 shows (a) the surface morphology for plasma and NB irradiation to the gate interface and (b) measured DC and gate-pulsed output characteristics. The results suggest that NB is applicable for the gate recess etching with suppressing the current collapse.

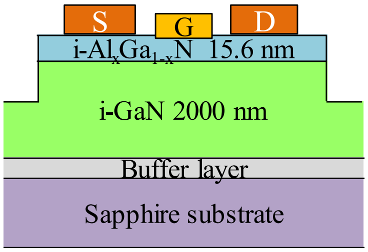
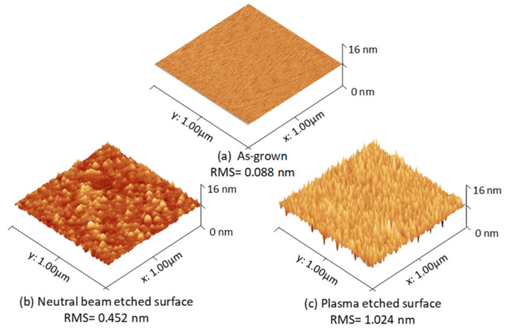
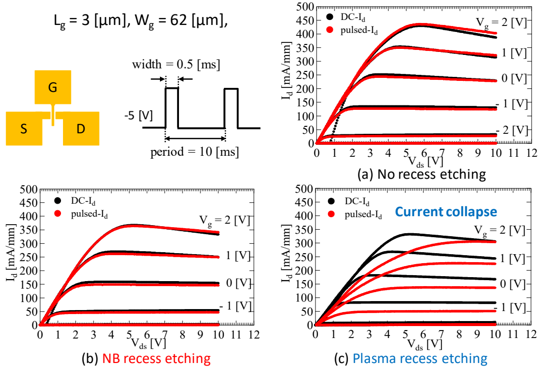


Fig. 6 A recessed gate structure as a way to realize normally-off operation in GaN, InP, and GaAs based HEMTs



(a) AFM images of gate recess surface



(b) Pulsed Id-Vds characteristics（Lg = 3 [μm]）

Fig. 7 (a) surface morphology for plasma and NB irradiation to the gate interface and (b) measured DC and gate-pulsed output characteristics.

4. High Efficiency Quantum InGaN Nano-disks LED

An advantage of the top-down process is that it can form nanostructures with an arrangement that can be uniformly controlled no matter what combination of materials is used. Instead of photolithography, we used a bio-template[9] as an etching mask with dots of a few nm in size. As shown in Fig. 8, the biological super-molecule (protein), ferritin has a diameter of 12 nm, and 7 nm internal cavity. There is a negative charge inside this cavity, and when ferritin is put into a solution containing dissolved Fe ions, these Fe positive ions are introduced into the cavity of ferritin molecules to form iron oxide cores. These iron cores are 7 nm in diameter. Ferritin molecules containing these iron cores are selectively placed in a two-dimensional arrangement on a silicon oxide film, and the protein is then removed by UV/ozone or heat processing, leaving behind the 7 nm iron cores on the substrate for use as an etching mask. Finally, Cl_2 based neutral beam can etch any kind of surface materials using the etching mask of 7 nm iron cores.[10]

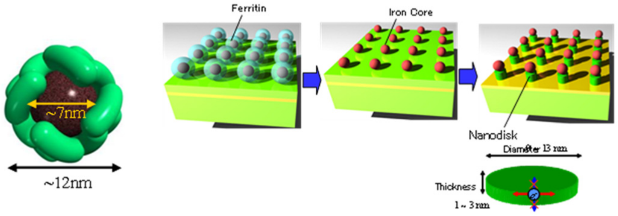


Fig. 8 Etching mask is made from iron cores encapsulated within the ferritin molecules.

We have demonstrated the fabrication of homogeneously distributed $In_{0.3}Ga_{0.7}N$/GaN quantum nanodisks (QNDs) with a high density and average diameter of 10 nm or less in 30-nm-high nanopillars by using bio-templates that were spin-coated on an $In_{0.3}Ga_{0.7}N$/GaN single quantum well (SQW) followed by defect-free neutral beam etching on ferritins with 7 nm diameter iron cores (Fig.9).[11] The photoluminescence measurements at 70 K showed a blue shift of quantum energy of 420 meV from the $In_{0.3}Ga_{0.7}N$/GaN SQW to the QND. The internal quantum efficiency of the $In_{0.3}Ga_{0.7}N$/GaN QND was 100 times that of the SQW. A significant reduction in the quantum-confined Stark effect in the QND structure was observed, which concurred with the numerical simulation using a 3D Schrödinger equation. These results pave the way for the fabrication of III−N quantum devices using nano-processing, which is vital for light emitting diodes (LEDs) and optoelectronic communication devices.

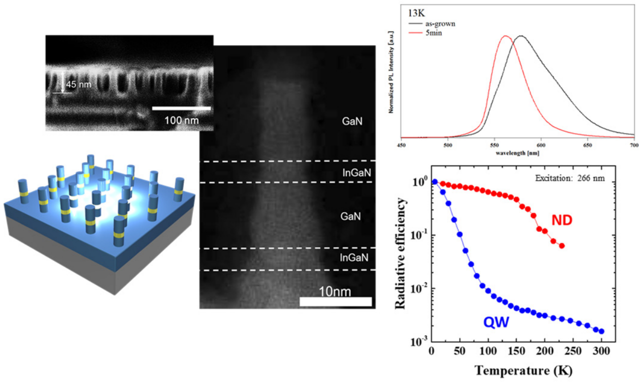


Fig. 9 PL spectra and IQE at various temperatures for $In_{0.3}Ga_{0.7}N$/GaN SQW and QND.

5. Conclusion

This paper has reviewed our research into cutting-edge nano-devices using the neutral beam etching. In the advanced nano-devices of the future, it will be essential to use ideal surface chemical reactions that do not cause surface defects and can be controlled at the atomic layer level. The neutral beam etching process is an intelligent nanoprocess that completely suppresses the ultraviolet rays and electrical charges emitted from a plasma, and is thus able to achieve ideal surface atomic layer reactions. We hope that this technique will make a large contribution to the development and implementation of new devices in the future.

6. Acknowledgments

We would like to acknowledge the assistance given by Prof. Tetsuya Suemitsu of Tohoku university in relation to GaN HEMT, Prof. Ichiro Yamashita of Nara Institute of Science and Technology, Prof. Akihiro Murayama of Hokkaido University, Prof. Kohei Ito of Keio University and Prof. Akio Higo of Tohoku University, Advanced Institute of Material Research in relation to the quantum nano-disks. This study was partly commissioned by the Japan Science and Technology Agency (JST) and has received funding to promote the CREST Project and the Revitalization Program. Our thanks to everyone concerned.

References

[1] T. Nozawa and T. Kinoshita, Jpn. J. Appl. Phys., 34, 2107 (1995).
[2] J.-P. Carrere, J.-C. Oberlin, and M. Haond, Proc. Int. Symp. on Plasma Process-Induced Damage (AVS, Monterey, 2000) pp. 164.
[3] T. Dao and W. Wu, Proc. Int. Symp. on Plasma Process-Induced Damage (AVS, Monterey, 1996) pp. 54.
[4] Mitsuru Okigawa, Yasushi Ishikawa, Yoshinori Ichihashi, and Seiji Samukawa, Journal of Vacuum Science and Technology, B22(6), 2818 (2004).
[5] S. Samukawa, K. Sakamoto, and K. Ichiki, Jpn. J. Appl. Phys., 40, L779 (2001).
[6] S. Samukawa, K. Sakamoto, and K. Ichiki, J. Vac. Sci. Technol., A20(5), 1566 (2002).
[7] S. Samukawa, B. Jinnai, F. Oda, and Y. Morimoto, Jpn. J. Appl. Phys.46, 3 (2007) pp. L64.
[8] F. Hemmia, C. Thomas, Y-C. Lai, A. Higo, Y. Watamura, S. Samukawa, T. Otsuji, T. Suemitsu, Solid-State Electron., vol. 137, 1(2017).
[9] I. Yamashita: Thin Solid Films 393 (2001) pp.12.
[10] T. Kubota, T. Baba, H. Kawashima, Y. Uraoka, T. Fuyuki, I. Yamashita and S. Samukawa, Journal of Vacuum Science and Technology, B23(2005) pp. 534.
[11] A. Higo, T. Kiba, S. Chen, Y. Chen, T. Tanikawa, C. Thomas, C. Y. Lee, Y-C. Lai, T. Ozaki, J. Takayama, I. Yamashita, A. Murayama, S. Samukawa, ACS Photonics, Vol. 4, 1851 (2017).

Acronym List

UV: ultraviolet
ALE: atomic layer defect-free etching
FWHM: full width at half maximum
AFM: atomic force microscopy
RF: radio-frequency
HEMTs: high electron mobility transistors
DC: direct current
LED: light emitting diode