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Effect of Inductively Coupled Plasma Etching in p-Type GaN Schottky Contacts

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The effects of inductively coupled plasma (ICP) etching damage on the electrical characteristics of low-Mg-doped p-GaN Schottky contacts were evaluated. The ICP etching greatly reduced the memory effect in the current-voltage characteristics and the difference between the depletion layer capacitances before and after forward current injection. These reductions indicate that acceptor-type interfacial defects were passivated by H atoms during ICP etching. Additionally, photoresponse (PR) measurements revealed that Schottky barrier height was increased from 2.08 to 2.63 eV by the etching. Because of the surface state change, the Fermi level position would be moved toward the conduction band edge slightly by the etching. After annealing, the memory effect and the capacitance change were partially restored, and the PR spectra showed less variation. Absorbed H atoms on the p-GaN surface might be released by annealing.

1. Introduction

A recent progress in the development of GaN-based optoelectronic devices, such as blue light-emitting diodes, laser diodes, and ultraviolet detectors, points to the need for better ohmic contacts to p-GaN and a deeper understanding of the basic characteristics of a metal/p-GaN interface. We have reported improved leaky characteristics for Ni/p-GaN Schottky contacts by low Mg doping and obtained a Schottky barrier height ($q\phi_B$) as large as 2.4 ± 0.2 eV from current-voltage (I-V) measurements.1) It is also found that surface Fermi level (E_F) pinning is strong and a large number of acceptor-type midgap defects (D_{mid}) are in the vicinity of the interface.2) Carrier capture and emission from D_{mid} localized in the vicinity of the interface cause depletion layer width (W_{dep}) to vary significantly. Upon the ionization of the defects by white light, which results in a small W_{dep}, current can go through the Schottky barrier and a leaky I-V curve is observed. Upon filling by current injection, W_{dep} increases and the large original $q\phi_B$ is seen. This reversible transition with a very long time constant of thermal emission from D_{mid} is called a memory effect.

As for device fabrication, an inductively coupled plasma (ICP) etching technique has been widely used in the mesa isolation of a p-n junction structure for not only optical devices but also electron devices, i.e., etching the GaN surface down to a base layer of npn bipolar transistors and a buried p-layer in field-effect transistors.3, 4) In these processes, p-layer surfaces would be affected by process-induced damage. To date, this type of damage has been evaluated by using the X-ray photoemission spectroscopy method (XPS), Schottky and metal/insulator/semiconductor diodes for n-GaN, and back-to-back diodes for p-GaN.5-11)

In this study, low-Mg-doped p-GaN Schottky contacts were used to evaluate ICP etching damage. Basically, the p-GaN Schottky contacts are expected to be sensitive to surface damage and conventional I-V, capacitance-voltage (C-V), and photoresponse (PR) methods can be used for characterization.

2. Experimental Procedure

In this experiment, we used free-standing GaN substrates in order to eliminate the effect of dislocations as much as possible. One-micrometer-thick undoped GaN films and 2-μm-thick low-Mg-doped GaN (Mg: 1×10^{18} cm^{-3}) films were grown on GaN-bulk substrates by metalorganic chemical vapor deposition, as shown in Fig. 1.

Figure 2 shows the experimental procedure of device fabrication. Firstly, using CH_2Cl_2 and Cl_2, ICP etching was carried out on p-GaN surfaces at depths of 20 and 200 nm at two different etching powers of 100 and 200 W for 1 min, respectively. In addition, half of the samples were annealed at 800 °C for 10 min in N_2 atmosphere. Then, after hydrochloric acid surface treatment, 60-nm-thick Ni films were deposited by electron beam evaporation to form Schottky contacts (200 μmϕ). Finally, large-area ohmic electrodes were formed by putting liquid-metal $In_{0.17}Ga_{0..83}$ on the p-GaN surfaces without annealing. We prepared 6 samples in total, including reference samples without ICP etching.

To investigate the memory effect more quantitatively, depletion layer capacitance (C_{dep}) was measured after light illumination in the dark (C_∞) and after applying a forward pulse voltage of -4 V for 1 min (C_0) at a DC bias of 0 V (see the inset in Fig. 4) using a precision impedance meter (HP 4284A).

In the PR measurements, when monochromatic light with a photon energy (hν) greater than $q\phi_B$ is incident on a metal/GaN interface, carriers in the metal can surmount the Schottky barrier and a photocurrent may be generated, which is called the internal photoemission effect. Schottky barrier height can be determined from the measured photoemission using Fowler's equation: [12)]

$$Y^{\frac{1}{2}} \propto (h\nu - q\phi_B), \qquad (1)$$

where Y is the measured photoemission yield. When hν is close to the band edge, owing to the generation of electron-hole pairs, a large photocurrent flows, as observed in a solar cell.

3. Results

3.1 I-V characteristics

Figure 3 shows typical forward I-V characteristics of the (a) unannealed and (b) annealed samples. After the illumination of the samples with white light, the I-V measurements with a voltage sweep from 0 to -10 V were consecutively conducted twice in the dark. As mentioned in the introduction section, as far as we have characterized low-Mg-doped p-GaN Schottky contacts, the I-V curves are different between the first and second sweeps. In this study, the memory effect was also observed for all the samples. For the unannealed samples without etching and with 20 nm etching, the memory effect is very large with onset voltages of -1 to -2 V for the first sweep and -5.0 to -5.5 V for the second sweep. However, the memory effect is greatly reduced by 200 nm etching. The onset voltages of the first and second sweeps are close at around -1.8 V. By annealing, the memory effect was reduced for the samples without etching and with 20 nm etching, but it was increased for the 200-nm-etched samples. The onset voltages of these three types of sample for the first sweep are almost the same at -1.2 V.

The reverse biased current was as low as around 1 pA at V = 10 V for all the samples, and the effects of etching and annealing were not observed.

3.2 Depletion layer capacitance

Figure 4 shows the measured depletion layer capacitances. Here, the amount of change (ΔC) from C_∞ to C_0 corresponds to the defect density. The unannealed sample without etching showed the largest ΔC from C_∞= 72 to C_0= 25 pF. For the etched samples, C_∞ greatly decreased. As a result of etching, the ΔC values are as small as 10 and 5 pF for 20-nm- and 200-nm-etched samples. Upon annealing, C_0 is around 30 pF for three types of sample, and the ΔC values are partially restored for the etched samples.

Figure 5 shows carrier profiles obtained from the C-V results. Basically, flat profiles were obtained. The unannealed samples showed an ionized acceptor concentration (N_A) of 2×10^{17} cm^{-3}, which consists of an activation efficiency of 20 %. After the annealing, N_A increased by 2-3 times.

3.3 PR spectrum

Figure 6 shows a PR spectrum, in which the square root of Y is plotted as a function of hν. No peak of the fundamental absorption near the band gap was seen, because the incident light was absorbed by the thick GaN substrate, and the generated electron-hole pairs did not reach the depletion layer. For all the samples, linear regions were observed in the lower energy side of the band edge. The obtained signals can be considered to be due to the internal photoemission. For the unannealed samples, the unetched samples showed the highest PR signal intensity. As the etching depth increased, the intensity decreased. After annealing, the sample-to-sample variation decreased.

Schottky barrier height was successfully obtained from the linear regions without suffering from characteristic variation by the memory effect in the I-V and C-V results. Figure 7 shows resultant $q\phi_B$ values from PR. Before annealing, $q\phi_B$ was 2.08 eV for the unetched samples. By 20 and 200 nm etching processes, $q\phi_B$ was increased to 2.49 and 2.63 eV, respectively. After annealing, as the PR spectra had less variation, $q\phi_B$ ranged between 2.22 and 2.32 eV.

4. Discussion

ICP etching greatly reduced the memory effect in the I-V and ΔC values. Two potential explanations can be considered; one is the passivation of D_{mid} by H atoms from the decomposed CH_2Cl_2 gas, and the other is compensation by donor-type defects formed during ICP etching. We also conducted the same experiments for n-GaN Schottky contacts. In the n-type case, the etching decreased $q\phi_B$ and increased C_{dep} and leakage current. These results can be explained by the creation of donor-type defects on the n-GaN surfaces. Zhang et al. reported $q\phi_B$ reduction and a low reverse breakdown voltage in n-GaN Schottky diodes caused by Cl_2/Ar ICP damage, due to the preferential loss of N atoms from the GaN surface that led to the creation of shallow donors.6) Hashizume and Nakasaki reported that H_2 plasma treatment induced the formation of N vacancies, whose energy level is located below the conduction band by 0.5 eV in metal/SiN/n-GaN diodes.7) The same phenomena may also occur on the GaN surfaces under our experimental conditions: however, as the N vacancy level is above E_F, defect compensation is essentially not effective for p-GaN contacts. Therefore, H_2 passivation is more likely.

From the PR results, E_F pinning is strong at the GaN surface, but the position is moved to the conduction band edge slightly by the etching. There are some reports on the surface band bending of p-GaN surfaces investigated by XPS measurements. Lin and Chu reported that band bending increased from 1.0 to 1.7 eV, and the leakage current was suppressed by reactive ion etching.5) In contrast, Jang and Lee reported that the bending decreased, but the leakage current remained suppressed by ICP etching.11) They suggested the formation of an n-GaN layer at the top surface. Our results supported Lin's report indicating that even Schottky contacts were formed on p-GaN surfaces.

Finally, the effect of annealing is discussed. As shown in the carrier profile, upon annealing, the Mg acceptors were activated much more. Accordingly, the forward currents in the voltage region below -5 V and the C_0 values increased. In general, it is assumed that the higher activation is caused by the dissociation and out diffusion of H atoms. On the basis of this assumption, if the surface defects are passivated by H atoms, the surface tends to be restored to its as-grown condition upon annealing; thus, ΔC is expected to increase and the PR spectrum is expected to show less variation.

For further studies, analysis of surface composition, investigation of the effect of only H_2 plasma surface treatment, and isothermal capacitance transient spectroscopy to characterize D_{mid} are planned.

5. Conclusions

The effects of ICP etching damage on the electrical characteristics of low-Mg-doped p-GaN Schottky contacts were evaluated. ICP etching greatly reduced the memory effect in the current-voltage characteristics and ΔC. These reductions indicate that acceptor-type interfacial defects were passivated by H atoms during ICP etching.

PR measurements revealed that $q\phi_B$ was increased from 2.08 to 2.63 eV by the etching. Because of the surface state change, E_F would be moved toward the conduction band edge slightly by the etching. After annealing, the memory effect and ΔC were partially restored, and the PR spectra showed less variation. The H atoms absorbed on the p-GaN surface might be released by annealing.

These results also tell us that the use of low-Mg-doped p-GaN Schottky contacts is suitable and sensitive for process-induced damage.

Acknowledgment

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Figure captions

Fig. 1. (Color online) Device structure with a configuration for PR measurements.

Fig. 2. (Color online) Device fabrication procedure.

Figs. 3. (Color online) Forward I-V characteristics of Ni/p-GaN contacts (a) without and (b) with annealing at 800 ℃ for 10 min.

Fig. 4. (Color online) Depletion layer capacitances with a measurement sequence. Solid and open symbols are for without and with annealing, respectively. The differences (ΔC) from fully ionized (C_∞) to neutralized (C_0) conditions correspond to the interfacial state density.

Fig. 5. (Color online) Calculated carrier profiles from the C-V results.

Fig. 6. (Color online) PR spectra in a wide photon energy range.

Fig. 7. (Color online) Summary of $q\phi_B$ values from the PR results.

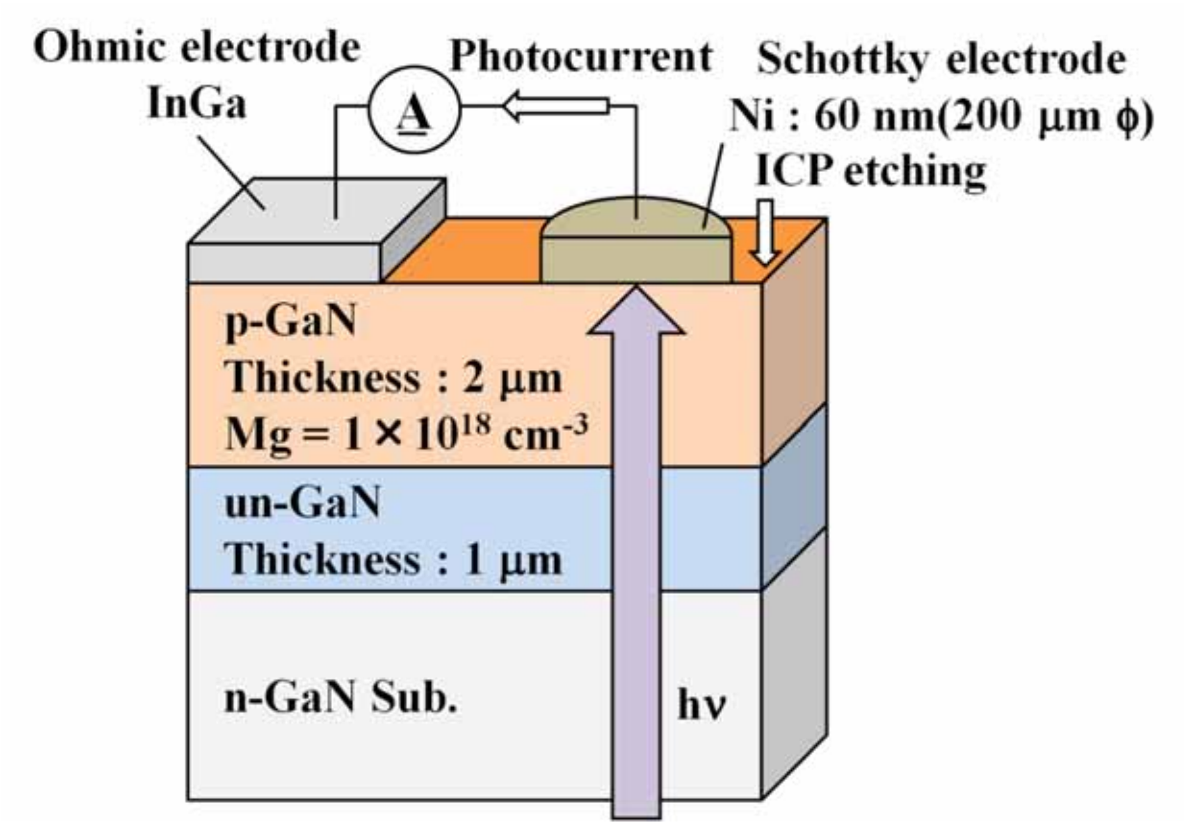

Ohmic electrode
InGa
A
Photocurrent
Schottky electrode
Ni : 60 nm(200 µm ϕ)
ICP etching
p-GaN
Thickness : 2 µm
Mg = 1 × 10^18 cm^-3
un-GaN
Thickness : 1 µm
n-GaN Sub.
hν

Fig. 1

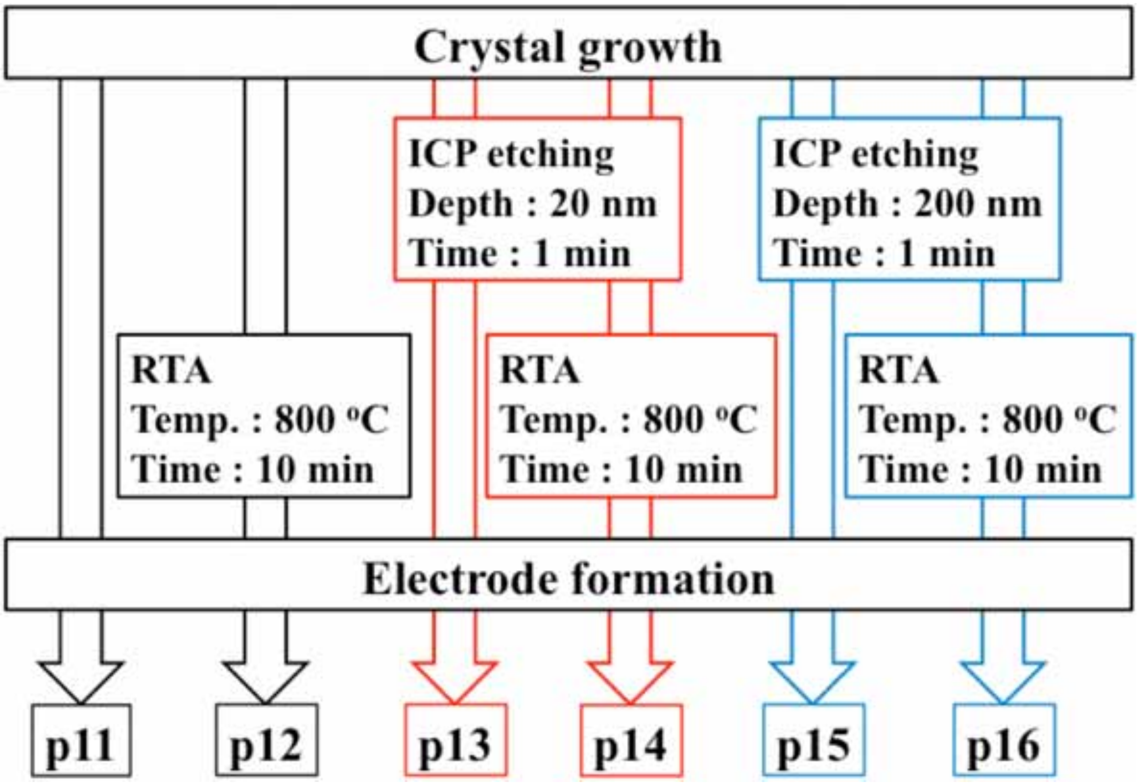
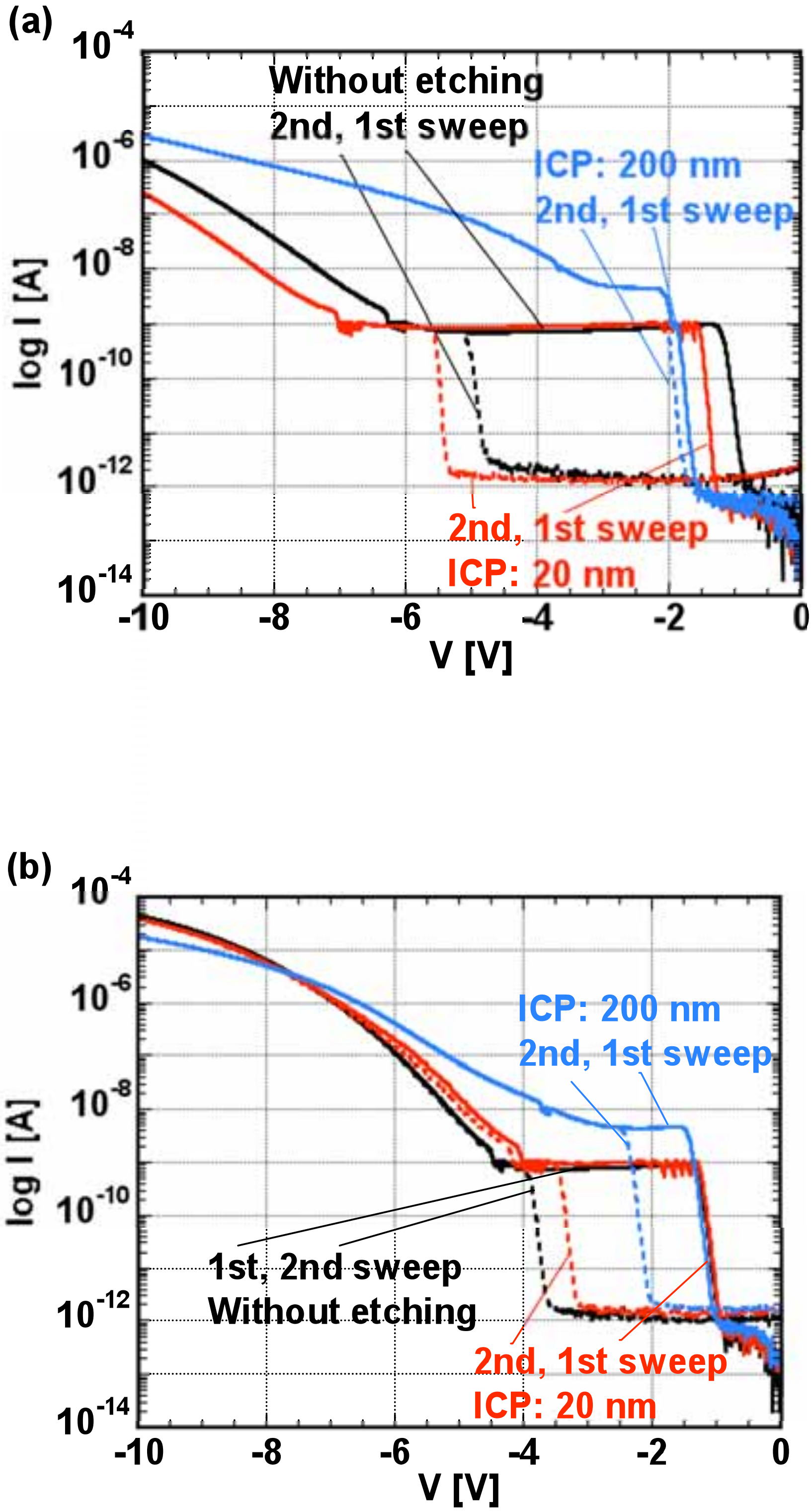

Crystal growth
ICP etching
Depth : 20 nm
Time : 1 min
ICP etching
Depth : 200 nm
Time : 1 min
RTA
Temp. : 800 °C
Time : 10 min
RTA
Temp. : 800 °C
Time : 10 min
RTA
Temp. : 800 °C
Time : 10 min
Electrode formation
p11
p12
p13
p14
p15
p16

Fig. 2


(a)
10^-4
10^-6
10^-8
10^-10
10^-12
10^-14
log I [A]
-10
-8
-6
-4
-2
0
V [V]
Without etching
2nd, 1st sweep
ICP: 200 nm
2nd, 1st sweep
2nd, 1st sweep
ICP: 20 nm
(b)
10^-4
10^-6
10^-8
10^-10
10^-12
10^-14
log I [A]
-10
-8
-6
-4
-2
0
V [V]
ICP: 200 nm
2nd, 1st sweep
1st, 2nd sweep
Without etching
2nd, 1st sweep
ICP: 20 nm

Figs. 3

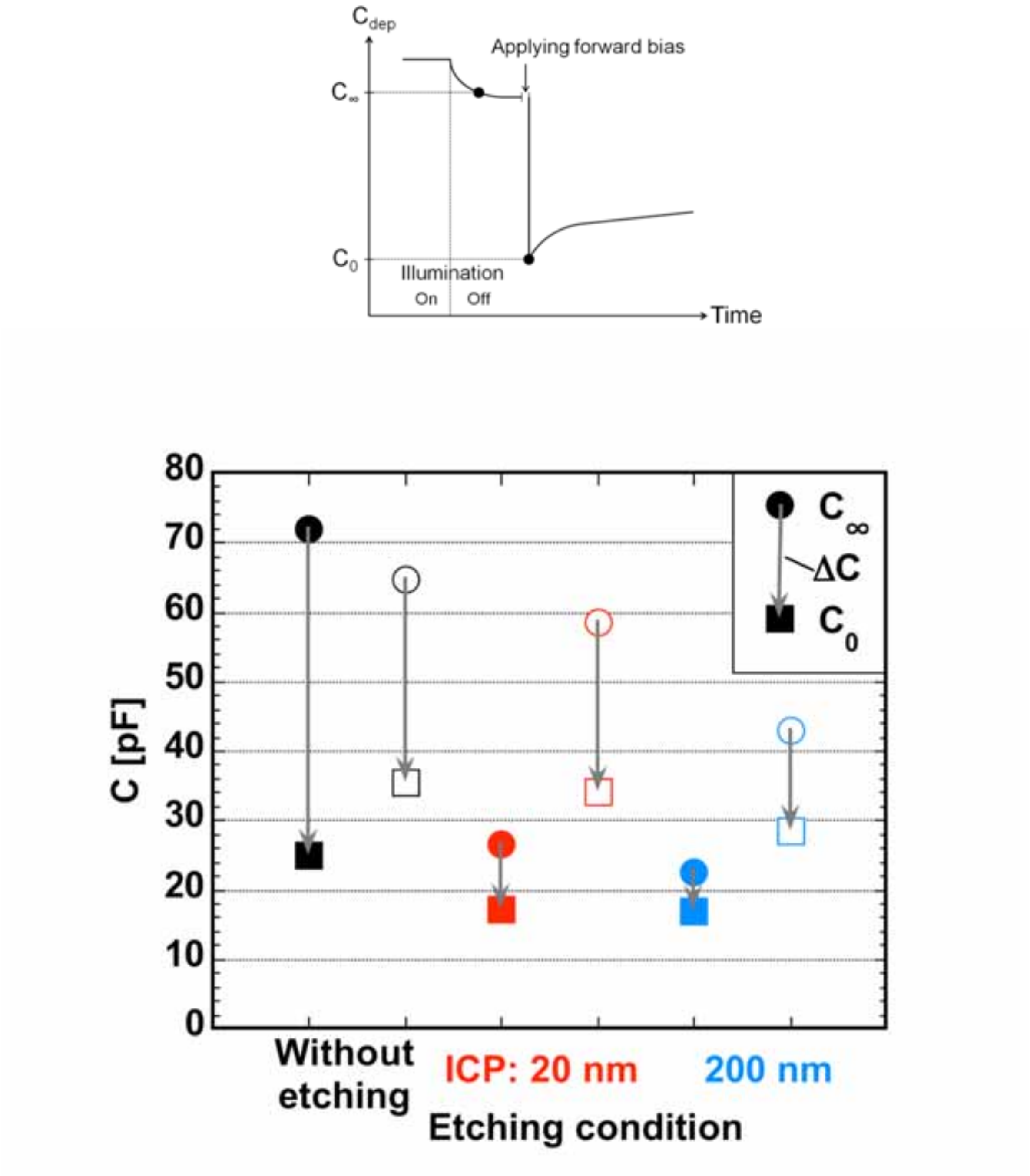
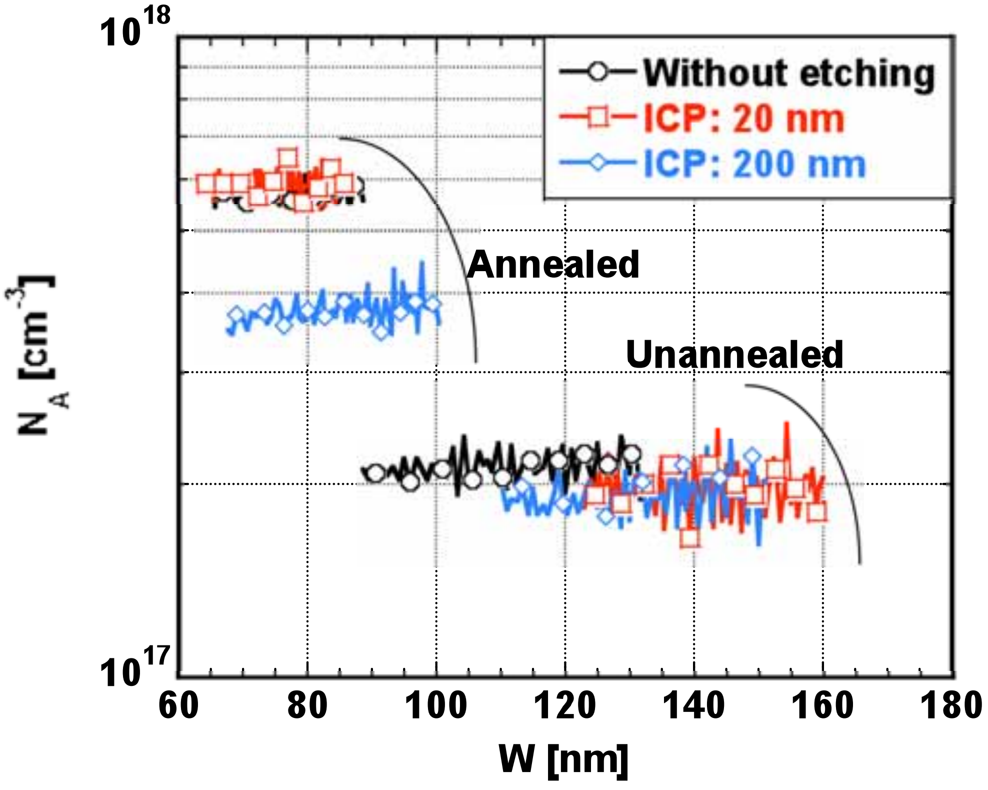

C_dep
Applying forward bias
C∞
C0
Illumination
On
Off
Time
80
70
60
50
40
30
20
10
0
C [pF]
C∞
ΔC
C0
Without etching
ICP: 20 nm
200 nm
Etching condition

Fig. 4



10^{18}
10^{17}
N_A [cm^{-3}]
W [nm]
60
80
100
120
140
160
180
Without etching
ICP: 20 nm
ICP: 200 nm
Annealed
Unannealed

Fig. 5

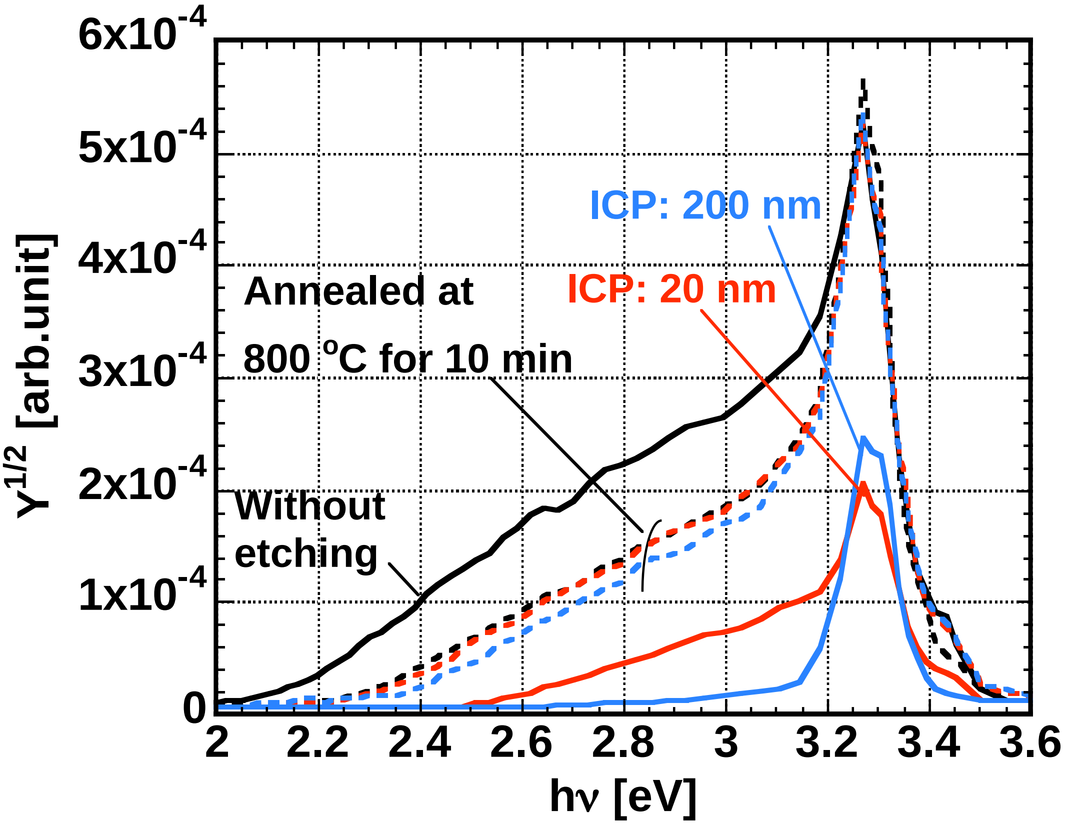

6x10^{-4}
5x10^{-4}
4x10^{-4}
3x10^{-4}
2x10^{-4}
1x10^{-4}
0
Y$^{1/2}$ [arb.unit]
2
2.2
2.4
2.6
2.8
3
3.2
3.4
3.6
hν [eV]
ICP: 200 nm
ICP: 20 nm
Annealed at
800 ^{o}C for 10 min
Without
etching

Fig. 6

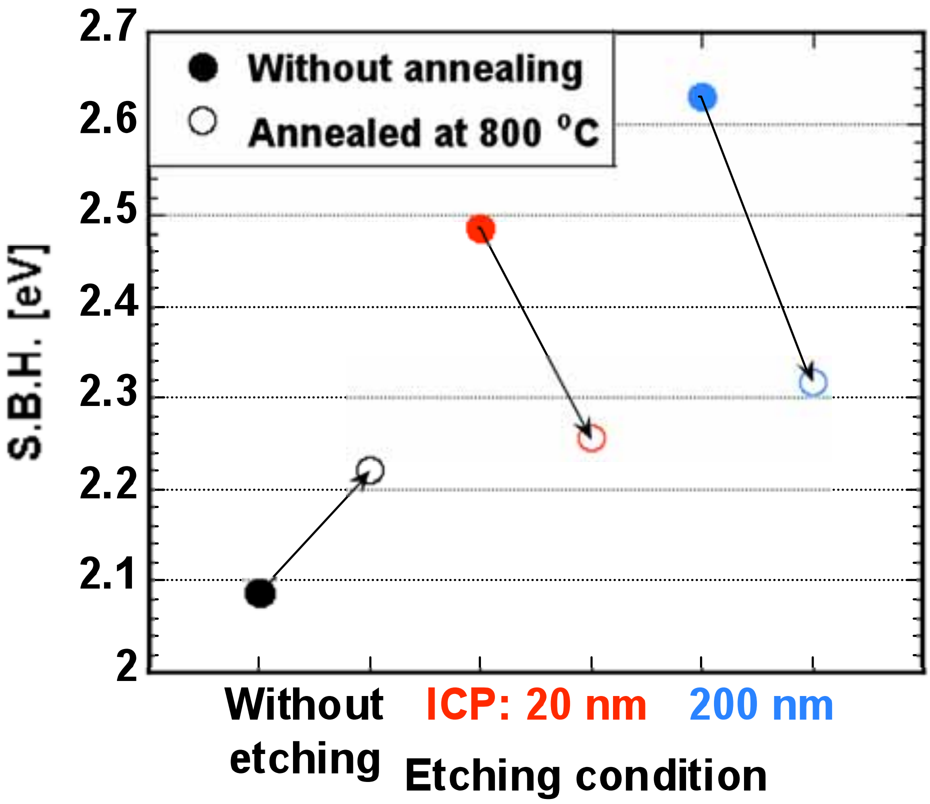

2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
S.B.H. [eV]
● Without annealing
○ Annealed at 800 °C
Without etching
ICP: 20 nm
200 nm
Etching condition

Fig. 7