2_Ion implantation into Gallium Nitride

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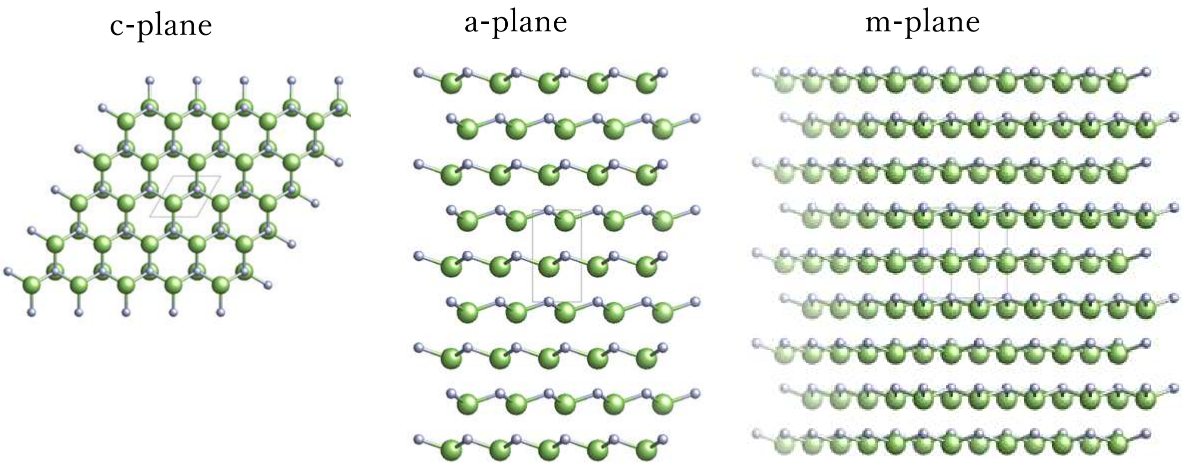
Among compound semiconductors, 4H-SiC has reached practical use. Recently, new devices such as super junctions using channeling are being developed. Channeling experiments on 4H-SiC have been conducted and compared with simulations (1). The phenomenon of Mg ion implantation into Gallium Nitride is now presented by using MARLOWE code.

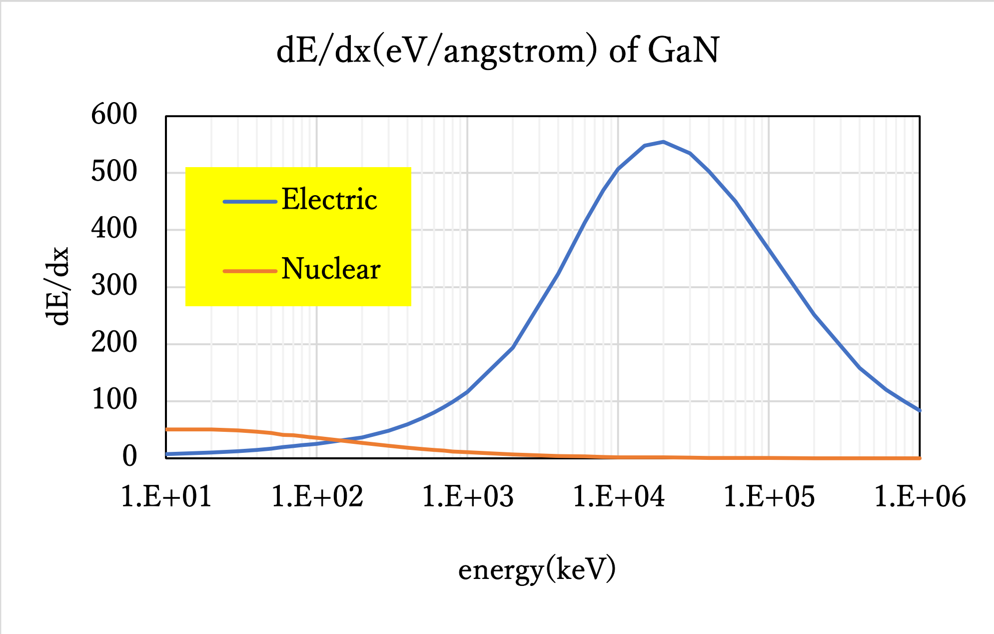
Crystal structure of Gallium Nitride

The crystal structure of Gallium Nitride is the Wurtzite system and the space group is classified as $P6_3mC$. The lattice constants are a-axis = 3.189 Å and c-axis = 5.1855 Å. The crystal structure when viewed from each crystal plane is shown below. This crystal model was created by the software called VESTA (2) and ReciPro (3).



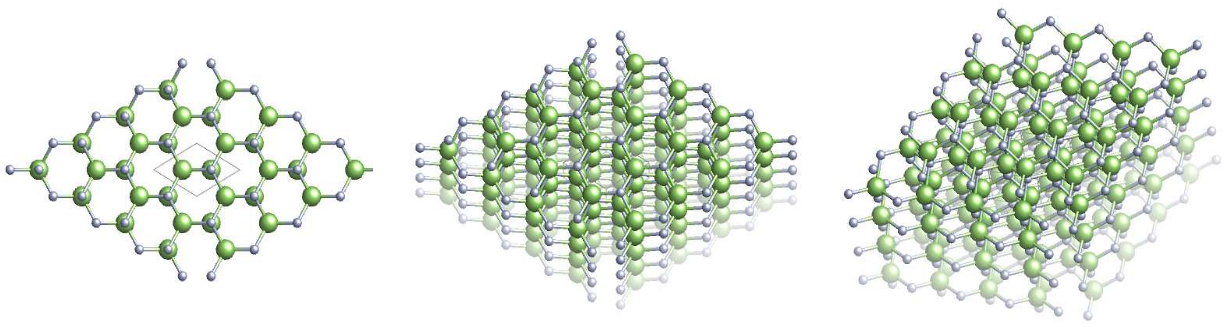
Ion implantation into Gallium Nitride

As explained in the previous article, the ion implantation phenomenon can be explained by the nuclear and electronic stopping power. The following graph shows the stopping power when Mg is injected into Gallium Nitride using the simulation code SRIM (4). The energy at which the nuclear stopping power and the electronic stopping power matches is around 150 keV. Below this energy, the stopping power of the nucleus is dominant, and above this energy the stopping power of the electrons is dominant.

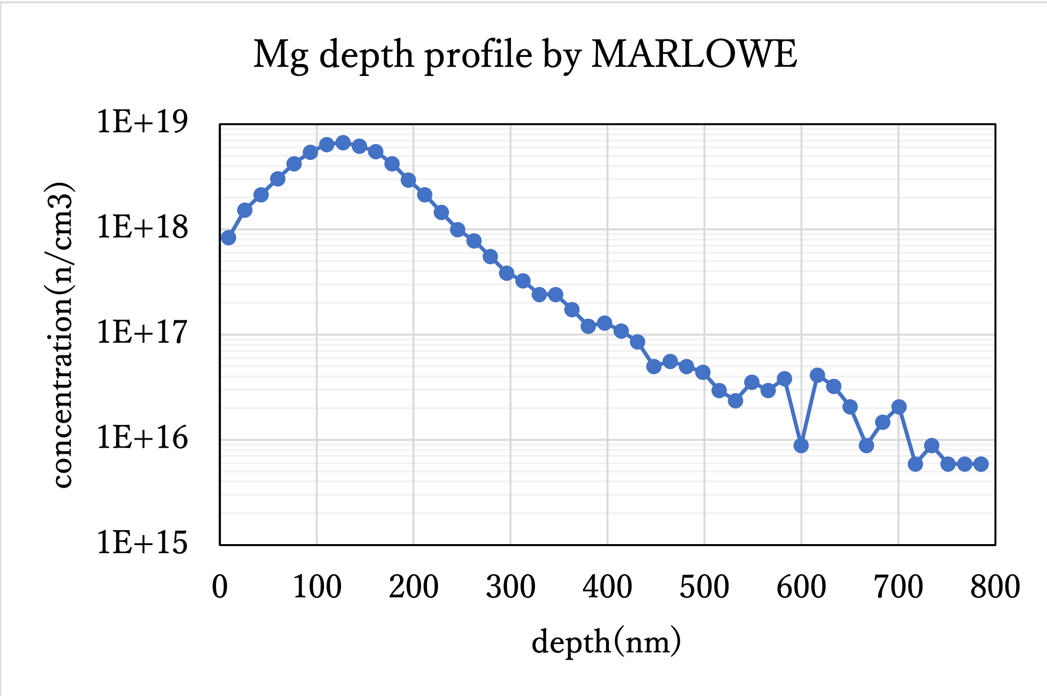


Considering the crystal structure, when ions are injected along the c-axis, a channeling phenomenon is likely to occur in which the ions pass deep into the substrate, and this phenomenon must be suppressed. The method for suppression of channeling is to deposit an oxide film to the surface or tilt the wafer. The figure below shows what it looks like from incident ions when the crystal axis is tilted. The figure on the left shows the channeling conditions when viewed along the c-axis. The figure in the center shows the case where the c-axis is tilted, but it can be seen that planar channeling occurs because there is clearly a region where ions pass through in the vertical direction. The figure on the right shows the case where the crystal is rotated in-plane to suppress planar channeling. From this figure, we can see that the random implantation can be realized.

Channeling Tilt Tilt + Rotation



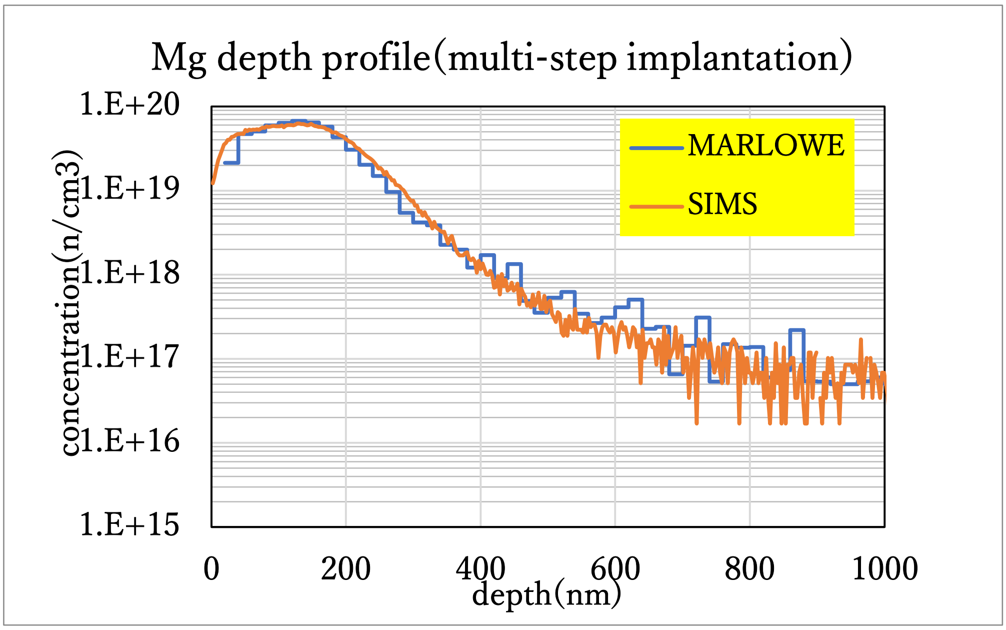
The following figure shows the profile in which Mg was injected under random implantation condition simulated by MARLOWE. The energy is 150 keV and the dose is 1E14 / cm2.



Furthermore, in order to achieve a constant concentration distribution in the depth direction, the multi-step implantation with different implantation energy and dose is used. For example, the implantation conditions for achieving a constant concentration at a depth of 200 nm are as follows.

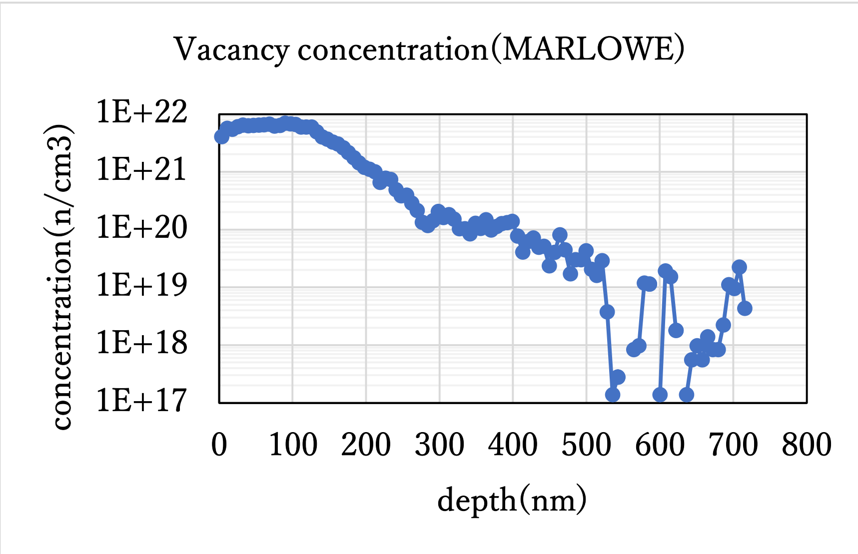
30keV 8E13/cm2
50keV 7E13/cm2
80keV 2E14/cm2
150keV 8.5E14/cm2

The following figure shows the Mg depth profile under this condition. As can be seen from the SIMS measurement results, the Mg concentration is constant up to a depth of about 200 nm. The analysis result by MARLOWE under the same conditions is also shown. Since MARLOWE code can handle targets with a crystal structure, it can be seen that even the tail region of the Mg depth profile can be reproduced.

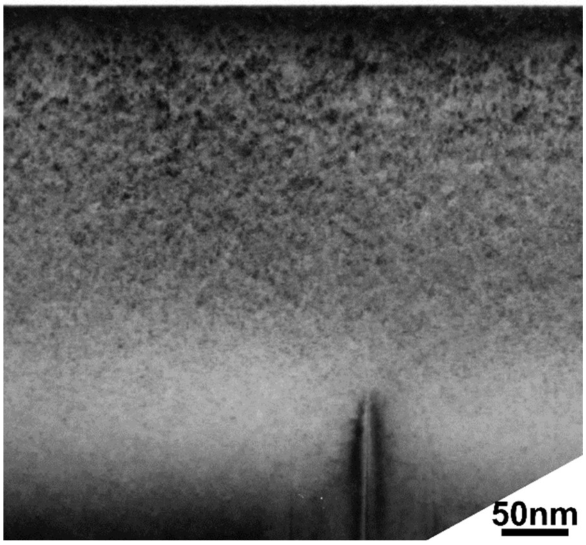


Damage by ion implantation

The figure below shows the vacancy distribution under the same conditions. Since the atomic density of Gallium Nitride is 8.8E21n / cm3, it is estimated that about 7% of the crystals are broken.



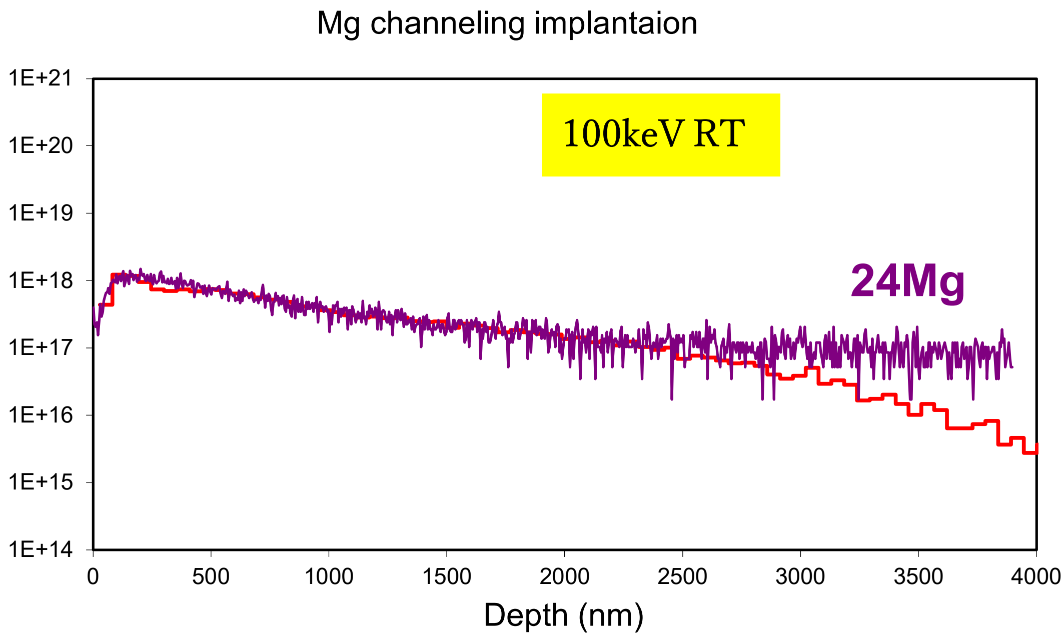
A cross-sectional TEM image in the case of multi-step implantation is shown (5). Since the region where the concentration of Mg ions is constant is about 200 nm from the surface, the dark contrast near the surface is considered to be vacancy or vacancy cluster caused by ion implantation.



It is difficult to realize high p-type activation(6). The reason of the low p-type activation seems that nitrogen vacancies created by implantation gather due to annealing to form vacancy complex and disturb defect recovery. Therefore, ion implantation with few defects is expected.

Channeling ion implantation

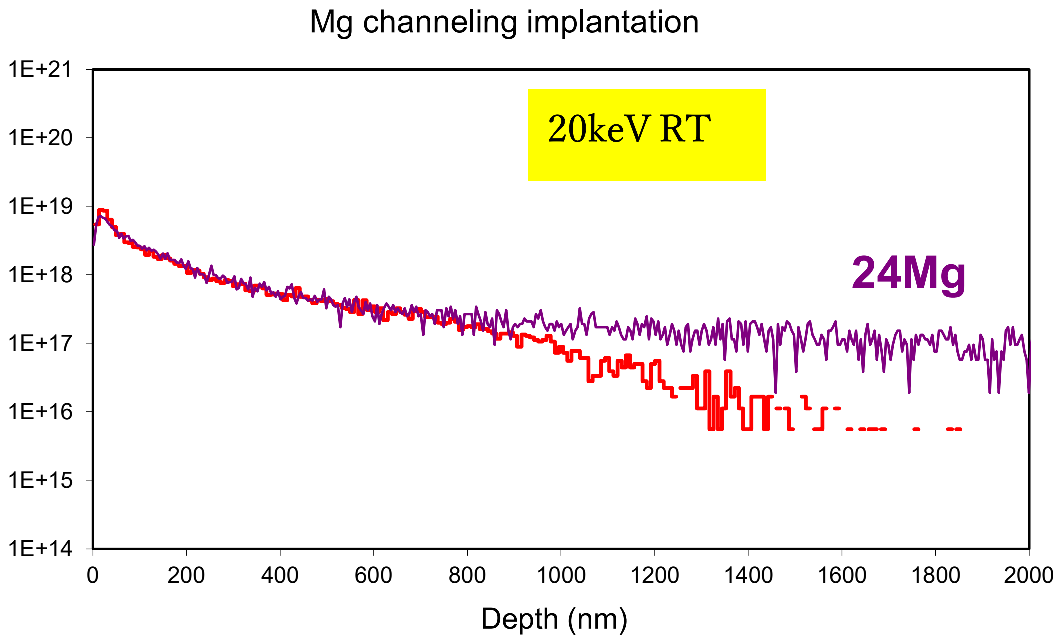
A feature of channeling implantation is that it can suppress defects deeply in ions. This is a method of implantation of ions along a specific crystal axis. We carried out the channeling implantation using the epitaxial Gallium Nitride sample. The result is shown below. The purple color shows the SIMS result, and the red step chart shows the result by MARLOWE code.

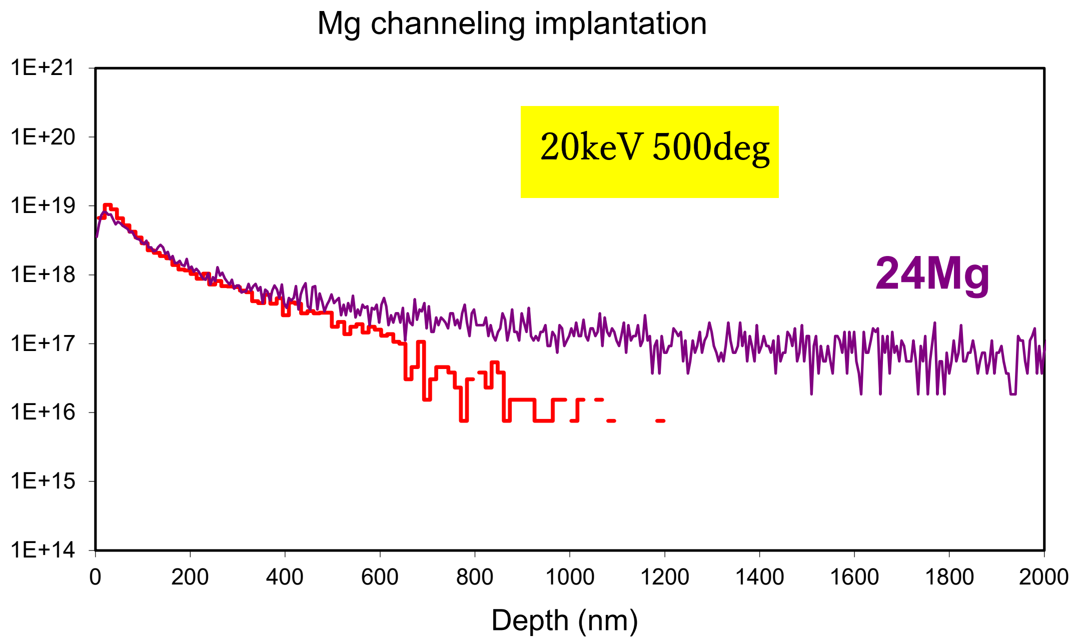


From this result, it can be seen that the SIMS measurement result can be reproduced up to the detection limit by MARLOWE code. The adjusted parameters are as follows.

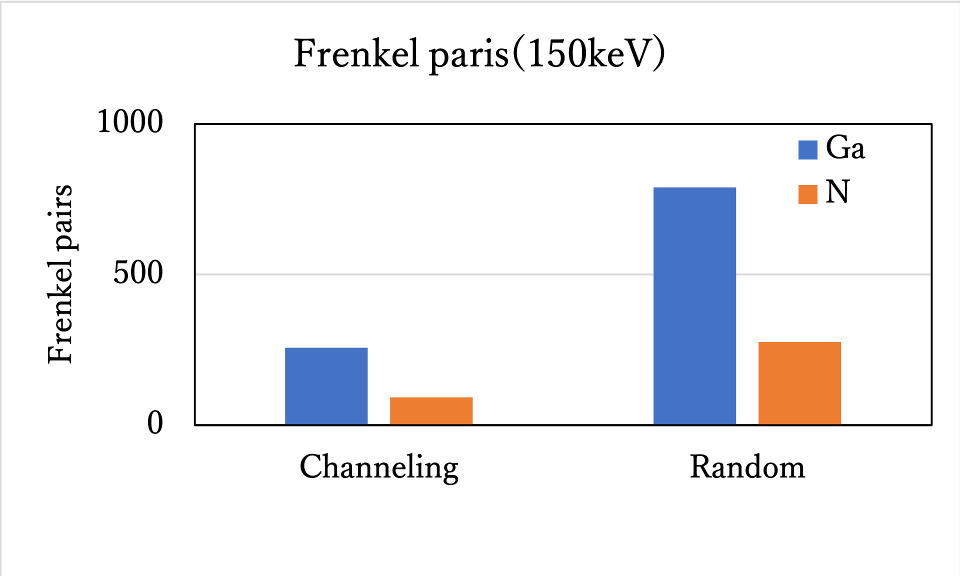
- Binding energy
- Rest energy
- Debye temperature
- Energy loss model
- Thickness of surface amorphous layer

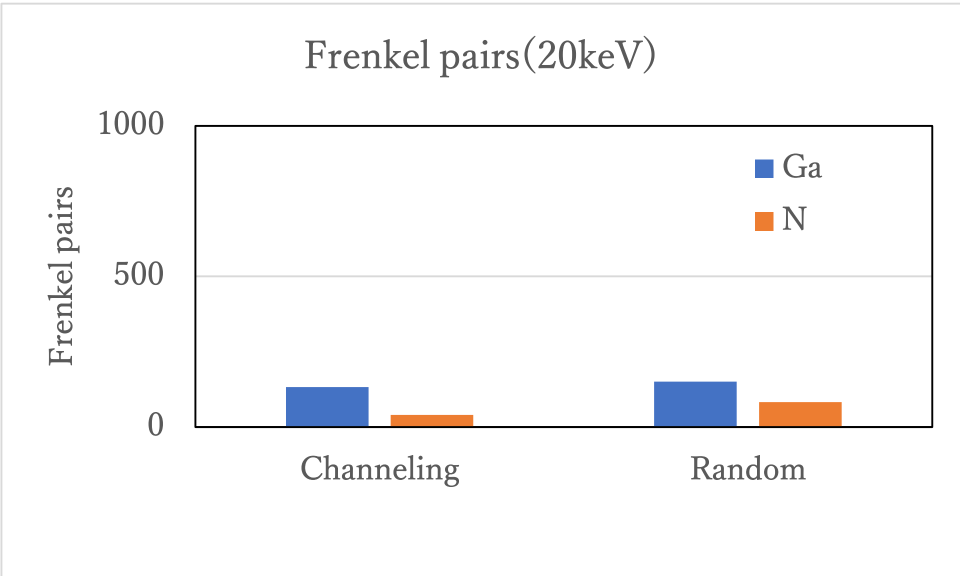
To evaluate the performance of MARLOWE, the energy was 20 keV and the substrate temperature was room temperature and 500℃. The results are shown below. In this case, you can see that the MARLOWE result can produce the SIMS result with high accuracy. In the case of 500℃ implantation, the Mg profile is shallower than in the case of room temperature, which is considered to be the result of the increase in the amplitude of the lattice vibration and the inhibition of the channeling phenomenon.


Mg channeling implantation
20keV RT
24Mg
1E+21
1E+20
1E+19
1E+18
1E+17
1E+16
1E+15
1E+14
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Depth (nm)


Mg channeling implantation
20keV 500deg
24Mg
1E+21
1E+20
1E+19
1E+18
1E+17
1E+16
1E+15
1E+14
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Depth (nm)

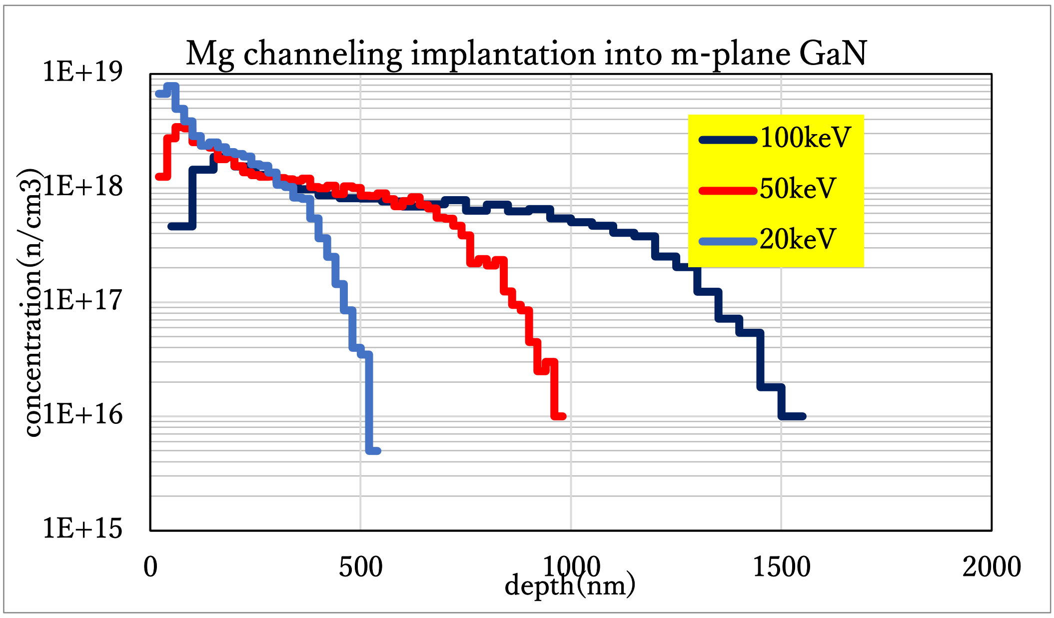
We will explain the difference between random implantation and channeling implantation from the viewpoint of defect formation. The bar graph below shows the number of Ga Frenkel pairs and the number of N Frenkel pairs caused by the collision cascades. Take the example of ion energy of 20 keV and 150 keV. It can be seen that the channeling implantation produces smaller defects in terms of the number of Frenkel pairs.





Ion implantation from the other crystal plane

Furthermore, when the crystal structure is viewed from the c-plane or a-plane and from the m-plane, it is presumed that the void region is narrower and the channeling phenomenon is more likely to be suppressed when viewed from the m-plane. When the channeling implantation from the m-plane was actually analyzed with MARLOWE code, it was found that the depth distribution was suppressed and the region with a constant concentration distribution was widened as shown in the figure below. It is said that the m-plane wafer is currently under development, but we hope it will be helpful as a possibility for new device development.



As described above, the ion implantation phenomenon into Gallium Nitride was explained using the analysis results by the MARLOWE code. Next time, we will introduce the presentation of ion implantation into Gallium Oxide, which is expected to make progress as a power semiconductor.

References

1) M. K. Linnarsson, et.al., Applied Physics A **volume 125**, Article number: 849 (2019)

2) K. Momma and F. Izumi, "VESTA 3 for three-dimensional visualization of crystal, volumetric and morphology data," J. Appl. Crystallogr., **44**, 1272–1276 (2011)

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5) J. Maekawa et. al., Materials Science Forum ISSN: 1662-9752, Vol. 1004, pp 497-504

6) T. Niwa, T. Fujii, and T. Oka, Appl. Phys. Express 10, 091002 (2017)

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