Verification for Aluminum Multi-Charged Ions Generation Using ECR Ion Source - Providing a Place to Improve Educational Effects Through Highly Motivated Active Learning -

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During semiconductor manufacturing, ions are injected into SiC, which is a common substrate material. Conventional ion-injection methods require high voltage to accelerate ions. This voltage can be decreased using multi-charged ions. In our laboratory, we can achieve ion injection via an electron cyclotron resonance ion source, which is relatively inexpensive compared with other ion sources and capable of generating multi-charged ions. The present research was conducted to improve the production rate of Ar7+, which has an ionization energy close to that of Al4+, and generate aluminum ions. The ion-extraction voltage and confinement time were optimized by adjusting the magnetic field in the chamber. The generation of aluminum ions could be confirmed using a sputtering source, and the usefulness of the latter was validated via the formation of the former. Research results were shared with plural KOSENs and the Nagaoka University of Technology students through Zoom, and we successfully confirmed the educational effect of the model core curriculum and development of the general-purpose abilities of the students.

1. Introduction

Ion injection is an indispensable technology in semiconductor manufacturing that enables the doping of impurities into a substrate material. The development of technologies to improve aluminum ion injection into SiC, which is a common substrate material, is a key aspect in improving a manufacturer’s competitiveness. Thus, we sought to conduct experiments to produce Al4+ using an electron cyclotron resonance (ECR) ion source. Previous research confirmed the generation of Ar7+, which has an ionization energy close to that of Al4+ (Al4+, approx. 120 eV; Ar7+, approx. 124 eV) [1].

The ultimate goals of this research are to generate Al4+ and apply the same to semiconductor manufacturing. The success of this research will help support the following sustainable development goals: “9. Industry, innovation and infrastructure” and “7. Affordable and clean energy.” Specifically, this research has two purposes: (1) to enhance the ion-beam current of Ar7+ and (2) to generate multi-charged aluminum ions.

The term “active learning,” which is indicated in the subtitle of this research, has attracted increased attention in the field of education from the viewpoint of dialog learning. We will utilize the joint research system of KOSEN–Nagaoka University of Technology. This learning theme is adopted
in the present research to improve students’ presentation skills by practicing active learning using the research results of our ECR ion source as educational material. In this case, improvements in the understanding of the research findings and increased opportunities for social interaction via education are desired.

2. Experimental Equipment and the Definition of Terms

2.1 Electron Cyclotron Resonance Ion Source

An ECR ion source is a high-intensity device that supplies multivalent ion beams. The characteristics of the resulting beams can be modulated and the material strength can be improved by varying the semiconductor element and irradiating ions. ECR ion sources are used in various fields. These ion sources are an indispensable technology for ion implantation in semiconductor manufacturing and play a key role in enhancing the capabilities of power semiconductors.

Figure 1 shows the components of the ECR ion source used in the present work. The device mainly comprises plasma-generating chambers, high-voltage electrodes for ion-beam magnets, mass-analysis magnets, Einzel lenses that converge the extracted ion beams, and a Faraday cup to collect the ion beams.

The ECR ion source confines the plasma in the chamber and uses a permanent magnet to introduce microwaves into the chamber. In a typical ECR ion source, the magnetic field is formed by a set of solenoid coils (mirror magnetic field) and six pole magnets. The ECR ion source used in our laboratory has a ring-shaped and an eight-pole permanent magnets. Moreover, three solenoid coils adjust the magnetic field in the chamber. The ability to adjust the magnetic field in the chamber is a key feature of ECR ion sources [1].

Electrons in the plasma are accelerated by ECR. This device constantly removes electrons from atoms and ions to generate multi-charged ions.

2.2 Definition of Terms

2.2.1 Active Learning

According to the glossary of the ministry of education, Culture, Sports, Science, and Technology [2], in contrast to the one-way lecture form of most teachers, active learning is a general term for teaching and learning methods that incorporate the active participation of learners in their studies. The approach aims to develop general-purpose abilities, including cognitive, logical, and social, as well as culture, knowledge, and experience, by encouraging active study among learners. Besides discovery,
problem-solving, experiential, and research learnings, group discussions, debates, and group work in classrooms are effective active learning methods.

Active learning in the present research refers to the sharing of our research results on the generation of multi-charged aluminum ions using an ECR ion source among different research groups after considering differences in the learning environment of the departments to which each KOSEN belongs. We aim to develop the general-purpose abilities of presenters and listeners by encouraging the free and active exchange of opinions. Specifically, we seek to promote logical-thinking ability through the sharing of research data, and presentations. Moreover, we wish to develop the cognitive and problem-solving abilities of other learners by providing experimental results, discussions, and question-and-answer sessions. Learners can accumulate experience by acquiring and practicing the knowledge necessary to understand and express the latter. We will evaluate learners’ knowledge acquisition using the model core curriculum and verifying its educational effects.

An important feature of the active learning presented in this research is that, unlike in general active learning, the students of the same generation with different specialties can exchange opinions freely. Thus, each learner can share their knowledge and culture and develop their general-purpose abilities.

2.2.2 Adviser
Advisers are individuals who review the content and method of a presentation and provide feedback to the presenter. In most cases, research leaders (e.g., the professor) act as advisers. In the question-and-answer sessions, the presenter may become aware of content problems through discussions. In this case, the questioner becomes an adviser of the presenter.

Advisers for listeners are individuals who listen to a presentation and supplement the information that the listeners did not understand. Specifically, these are the students of the same KOSEN, graduate students, and laboratory members.

3. Experimental Parameters and Evaluation Methods
3.1 Improvement in Ion-Beam Currents
In this experiment, we verified the generation efficiency of $\text{Ar}^{7+}$ by varying the z-axis mirror magnetic field (i.e., the magnetic field in the chamber), chamber (i.e., extractor) voltage, and voltage applied to the Einzel lens to focus the extracted ion beam. The parameters of this experiment are shown in Table 1.

\begin{table}
\centering
\begin{tabular}{|c|c|}
\hline
Solenoid Coil 1 & Solenoid Coil 2 & Solenoid Coil 3 \\
\hline
\text{Coil 1} = 0 A, \text{Coil 3} = 0 A & \text{Coil 1} = 0 A, \text{Coil 3} = -100 A & \text{Coil 1} = 200 A, \text{Coil 3} = -100 A \\
\text{Coil 1} = 100 A, \text{Coil 3} = 0 A & \text{Coil 1} = 0 A, \text{Coil 3} = -200 A & \text{Coil 1} = 200 A, \text{Coil 3} = -100 A \\
\text{Coil 1} = 200 A, \text{Coil 3} = 0 A & \text{Coil 1} = 200 A, \text{Coil 3} = -100 A & \text{Coil 1} = 0 A, \text{Coil 3} = -100 A \\
\hline
\end{tabular}
\caption{Experimental Parameters}
\end{table}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{magnetic_field_distribution.png}
\caption{Magnetic field distribution in the chamber}
\end{figure}

* The background figure is an image of the positional relationship of the z-axis.
A solenoid coil was used to adjust the magnetic field in the chamber. Figure 2 shows the magnetic field distribution in the chamber. As the current flowing into solenoid Coil 1 increased, the magnetic field around it became stronger. The corresponding magnetic field in solenoid Coil 3 weakened, and ion-beam extraction could easily be achieved.

3.2 Generation of Charged Aluminum Ions

The method adopted in this research to generate aluminum ions was sputtering. Sputtering causes accelerated ions to collide with a target, and the kinetic energy of these collisions causes atoms to be emitted from the surface of the target. As the emitted atoms are confined in the plasma, electrons are removed and ionized.

Sputtering is a typical thin-film forming technique. When forming a metal thin film, the metal target is sputtered in a noble gas atmosphere [3]. By comparison, when forming a compound thin film, such as an oxide or nitride, compound targets are sputtered in a noble gas atmosphere, and metal targets are sputtered in an atmosphere containing a reactive gas, such as oxygen or nitrogen [4-7]. The latter is called reactive sputtering. Herein, in addition to the ions, a material gas also collided with the target, and the resulting dissociation product chemically reacted with the target surface [8]. Ar, which is an inert gas, was used to avoid the formation of a compound thin film on the target surface.

In the present research, Ar was used as the sputtering gas, and multi-charged aluminum ions were generated using the parameters shown in Table 2.

3.3 Verification of Active Learning and Educational Effects

We created an evaluation questionnaire based on the model core curriculum established by the National Institute of Technology to assess the level of understanding of students. This questionnaire had four main components: (1) the level of understanding of the presentation contents (self-evaluation, 10 levels, average of 5), (2) presence of the adviser, (3) level of understanding following adviser intervention (self-evaluation, 10 levels, average of 5), and (4) free description. Presenters
combined the contents of the model core curriculum and their own research findings in their presentation.

An example of the combination of the content of the present research and model core curriculum is as follows. The knowledge described in “V-C-2 Electromagnetic, Current, and Magnetic Fields” is required to understand the principle behind “magnet analysis,” which is used for the mass spectrometry of ion beams. Moreover, the knowledge of “V-C-4 Electronics, Electron Properties, and Atomic Structures” is required to generate multi-charged ions.

4. Results and Discussion

4.1 Improvements in Ion-Beam Currents

Figure 3 shows the changes in the Ar\textsuperscript{7+} ion-beam currents as a function of the magnetic field in the chamber. Among the combinations of solenoid coil currents shown in Table 1, the combination of Coil 1 = 50 A and Coil 3 = -100 A yielded the largest Ar\textsuperscript{7+} beam currents (49.3 nA). When the magnetic field in the chamber by the solenoid coil was not adjusted, the Ar\textsuperscript{7+} beam current was only 17.0 nA. Adjusting the magnetic field in the chamber could increase the beam current up to 32.3 nA. The graph showed no regularity, and the Ar\textsuperscript{7+} ion-beam current fluctuated. Variations in the Ar\textsuperscript{7+} current may be related to the ease of ion-beam extraction by the mirror magnetic field in the z-axis direction and the plasma (ion) confinement time.

According to the literature [9], the beam current of multi-charged ions is expressed by the following equation:

\[ I_q \approx \frac{1}{2} \frac{n_q q e V \text{Vol}}{\tau_q}, \quad (1) \]

where \( n_q \) is the density of ions in the charged state \( q \); \( \tau_q \) is the confinement time of these ions, which depends on the potential dip \( \Delta \phi \); and \( V \text{Vol} \) is the volume of hot plasma mapped along the magnetic field lines into the extraction area.

From equation (1), if the confinement time of the ions is short, the ion-beam electric current increases; otherwise, increasing the density and plasma volume of \( q \) may be necessary. To change the magnetic field in chamber via solenoid coil, the magnetic field of the extraction electrode weakens, and the ion enclosure time decreases; thus, the electric current of the ion beam increases.

Decreases in the ion-beam electric current may be explained as follows.

Assuming plasma charge neutrality,

\[ n_e = \sum_q n_q q \quad (2). \]

Equations 1 and 2 yield Equation 3:

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3.png}
\caption{Changes in ion beam electric current as a function of the magnetic field in the chamber}
\end{figure}
Thus, the production of high-intensity \( I_q \), high-charge-state \( q \) ions is the result of the interplay between the ionization and plasma confinement conditions [3]. For normal, electrons are drawn to the opposite side of the extraction electrode. However, some electrons may remain in the plasma without being drawn under the influence of the magnetic field in the chamber. It recombines with the cations in the plasma, which is reduce the ion-beam electric current, may occur. Moreover, in a plasma confined in an electromagnetic field, the longer the confinement time, as for the ion, the possibility of recombination with electrons increases.

The above equations demonstrate that ion beams may easily be extracted by decreasing the magnetic field in the extractor electrode side of the chamber. The ion-confinement time decreases as the ion beam is extracted, and the ion-beam current fluctuates. Therefore, optimizing the strength of the magnetic field confining the ions (plasma) and voltage of the extractor electrode is necessary to maximize the ion-beam current.

4.2 Generation of Multi-Charged Aluminium Ions

Figure 4 shows the relationship between the sputtering voltage and \( \text{Al}^{+} \) current. When the sputtering voltages were –50, –100, –200, –300, and –400 V, the \( \text{Al}^{+} \) currents were approximately 0.01, 0.014, 0.033, 0.048, and 0.06 \( \mu \text{A} \), respectively. These results clearly show that the \( \text{Al}^{+} \) current increased proportionally as the sputtering voltage increased.

Figure 5 shows changes in the spectrum when the sputtering voltage varied from –100 to –400 V. It also shows an enlarged view of close the mass-to-charge ratio of \( \text{Al}^{+} \) (m/z = 27). The vertical axis represents the current (\( \mu \text{A} \)), and the horizontal axis shows the mass-to-charge ratio. The mass-to-charge ratio refers to the mass of an atom divided by its charge number (i.e., \( 27/1 = 27 \) for \( \text{Al}^{+} \), \( 40/7 = 5.71 \) for \( \text{Ar}^{7+} \)).

The figure shows that \( \text{Al}^{+} \) could be detected at approximately 0.06 \( \mu \text{A} \) when the sputtering voltage was –400 V. \( \text{Al}^{2+} \) (m/z 13.5) could not be identified because it has a mass-to-charge ratio close to that of \( \text{Ar}^{3+} \) (m/z 13.3). \( \text{Al}^{3+} \) could not be confirmed because of background noise. Similar to the generation of multi-charged \( \text{Ar} \) ions, the amount of \( \text{Al}^{2+} \), \( \text{Al}^{3+} \), and \( \text{Al}^{4+} \) generated may be expected to increase as the \( \text{Al}^{+} \) current increases. Therefore, confirming more than doubly charged ions was difficult because the \( \text{Al}^{+} \) current was very low.

The insufficiency of the \( \text{Al}^{+} \) current in the present experimental system may be attributed to the limited supply of aluminium atoms to the plasma confined in the magnetic field in the chamber.

Therefore, we are currently exploring the use of hybrid-type supply and evaporation sources in addition to the sputtering source to increase the \( \text{Al}^{+} \) current generated using the ECR ion source.

![Fig. 4](image1.png)  
**Fig. 4** Relationship between sputter voltage and \( \text{Al}^{1+} \) current

![Fig. 5](image2.png)  
**Fig. 5** Changes in the mass spectrum of multi-charged aluminium ions generated through sputtering
Although the Al⁺ current detected was not especially large, our results confirm the usefulness of the sputtering source.

4.3 Verification of Active Learning and Educational Effects
The research results were reported via two Zoom meetings on Oct. 15 and 22, 2020. After the research background and results were presented, a questionnaire survey was conducted. The results of the questionnaire are shown in Figure 6.

First, the presenter prepared their presentation slides. The level of understanding at this time was fairly low. After the presenter received advice from their supervisor, their level of understanding was assessed again. The presenter then presented the research content to the listeners. The listeners participated in the presentation and then evaluated their level of understanding without an adviser. Following a question-and-answer session conducted by the adviser, the listeners assessed their level of understanding (self-check) again. Differences in the levels of understanding throughout this process are shown from left to right in Figure 6.

In Figure 6, the numbers in the parentheses located to the right of the listener label indicate the number of people who participated in the presentation. The fairly large standard deviation of the level of understanding of listeners on Oct. 15 may be explained by the viewpoint of one listener: “Somehow, I can understand about analyzing magnet. But I cannot understand clearly. Moreover, they do not take the electrical engineering and electronic engineering lectures necessary to understand the research content due to the difference in the department they belong.”

The presenter received advice from their adviser on ways to improve their level of understanding and knowledge before a presentation. However, differences in the level of understanding may exist between the presenters and listeners. In the present case, we believe the presenter may not have understood some of the research content completely.

Compared with that in the first presentation, the overall level of understanding level in the second presentation improved probably because the presenter was aware of potential difficulties based on their experience in the initial presentation. As the listeners were presented with the same subject matter in the second presentation, their level of understanding improved. Thus, the input of the adviser and presentation experience improved the level of understanding of both the presenter and listeners.

The above results imply that different specialties can cause remarkable differences in the evaluation of the same model core curriculum. In this case, reviewing the presentation method and approach may be necessary. Sufficient preparation and experience are also recommended.

The effect of active learning is gradually enhanced by repeated practice. We confirmed the educational effect of the model core curriculum by explaining the research content to the students;

![Graph showing changes in comprehension level](image)

**Fig. 6** Changes in the comprehension level of the presenter/listeners through active learning
improved comprehension was generally observed, except in cases where differences in the departments to which the students belonged existed.

5. Conclusion

This research aimed to produce multi-charged aluminum ions for semiconductor manufacturing applications. Specifically, we sought to improve the production rate of $\text{Ar}^{7+}$, which has an ionization energy similar to that of $\text{Al}^{4+}$, and confirm the production of multi-charged aluminum ions. Moreover, we verified the development of the general-purpose abilities of students by sharing our research results with other research groups.

The adjustment of the magnetic field in the chamber could improve $\text{Ar}^{7+}$ production by enhancing the ion-extraction voltage and ion-confinement time. We confirmed the generation of aluminum ions using a sputtering source. However, the generation of multi-charged aluminum ions could not be verified because of the small amount of ions produced.

Repeated presentations greatly contribute to the development of the general-purpose abilities of students. We confirmed the educational effect of the model core curriculum by explaining the research content to a panel of students; improved comprehension was generally observed, except in cases where differences in the departments to which students belonged existed.

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References


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