Analysis of Compound Semiconductor and Copper Alloy Using Three-Dimensional Atom Probe

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ABSTRACT Three-dimensional atom probes were used to analyze dopants in compound semiconductors and precipitates in copper alloys. In the analysis of semiconductors, this method enables us to visualize dopant distribution on a nanoscale. In the analysis of copper alloys, the shape, size, and composition of precipitates of several nanometers can be analyzed in three dimensions.

1. INTRODUCTION

In the development and manufacture of compound semiconductor devices used in optical communication products, it is essential to confirm whether they are fabricated as designed. Transmission Electron Microscopy (TEM) is a commonly used method for observing semiconductor device structures at high magnification and is used not only in research and development but also in product management. On the other hand, a method for analyzing dopants, which are trace impurities that control the electrical properties of semiconductor devices at the nanoscale, is desired. However, it is usually difficult to analyze dopants below 0.01 atom% with Energy Dispersive X-ray Spectroscopy (TEM-EDX) due to limitations in detection sensitivity.

In the analysis of copper alloys, the required properties include strength, electrical conductivity, thermal conductivity, and workability. One of the copper alloys that meets these required properties is the Cu-Ni-Si alloy, and it is known that the strength is improved by finely dispersing Ni-Si compounds in the copper matrix by heat treatment. This Cu-Ni-Si alloy is called a Corson alloy and has both high strength and high conductivity. Currently, various Cu-Ni-Si alloys with improved properties have been developed by adding various additives and are widely used in electronic devices, such as smartphones, and are becoming an indispensable metal material in modern life. To improve the properties of this Cu-Ni-Si alloy, it is important to optimize the structure of the Ni-Si precipitates and to understand the shape and size of these precipitates.

Three-Dimensional Atom Probe (3DAP) is a method that can perform three-dimensional analysis of dopants in

compound semiconductors and precipitates in copper alloys on a nanoscale. 3DAP is not as versatile as TEM, but when used appropriately, it can provide analytical results that are difficult to obtain with TEM, and can be used in the development of new semiconductor devices and copper alloys.

2. THREE-DIMENSIONAL ATOM PROBE

2.1 Field Ion Microscopy (the technology that led to the creation of 3DAP method)

Three-Dimensional Atom Probe method (3DAP), or Atom Probe Tomography (APT), is a quite unique technique that can be roughly describes as follows: A high voltage is applied to a needle-shaped sample with a radius of curvature of about 50 nm, and a voltage pulse or laser pulse is used as a trigger to simultaneously measure the mass and the position of atoms ionized from the outermost surface, making it possible to visualize the atomic distribution in three dimensions at a magnification of about 2 million times. Although the analyzable volume is limited to a maximum of 1 µm, the spatial resolution is high enough to resolve atomic planes and the detection sensitivity is high, around 0.001 atom%, contributing to the clarification of the mechanisms by which trace amounts of added elements affect the functionality of materials and devices. To understand the principles of the 3DAP method, it is natural to first explain the underlying technology, the Field Ion Microscopy (FIM). When a high voltage is applied to a sharply pointed needle, a high electric field is generated at the tip of the needle sample. When a voltage V is applied to a needle with a radius of curvature r, the electric field F on the surface of the tip of the needle is described as¹⁾⁻⁵⁾

$$F = V/kr.$$
 (1)

Where k is a constant that depends on the shape of the sample and the distance from the electrode, and is usually 2–10. The three main phenomena that occur on surfac-

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es subjected to high electric fields are (1) field emission, (2) field ionization and (3) field evaporation. "Field emission" is a phenomenon that occurs when a "negative" electric field is applied to the sample surface. When a high voltage is applied to a needle-shaped sample, a high electric field is applied to the tip surface, which causes electron emission due to the electron tunneling phenomenon. Field Emission Microscopy (FEM) enables the emitted electrons to be observed on a fluorescent plate, and the field emission phenomenon is also used as an electron source in the Scanning Electron Microscopy (SEM) and TEM^{6), 7)}. Conversely, when a "positive" electric field is applied, a phenomenon called "field ionization" or "field evaporation" occurs^{1)-5), 8).} FIM is a technique that uses this phenomenon to observe surfaces. It was invented in 1951 by Dr. E.W. Mueller of Pennsylvania State University, and enabled mankind to observe images of atoms for the first time⁸⁾. Figure 1 shows a schematic diagram of FIM and an image of a tungsten needle observed using an actual FIM device. A positive voltage is applied to a needle-shaped sample cooled to several tens of K in a vacuum chamber, while an imaging gas such as helium or neon is injected at approximately 10⁻³ Pa. The imaging gas atoms are attracted to the needle-shaped sample surface under a high electric field and are then bounced off the cooled sample surface while losing kinetic energy. The imaging gas atoms are bounced back and forth several times, losing kinetic energy due to cooling, and when they reach a certain distance from the surface, they lose electrons due to tunneling and become ions. These ions are accelerated by the electric field between the sample surface and the fluorescent screen, and collide with the fluorescent screen, causing a bright spot to be observed. However, because the brightness of the ions is extremely low, a charged particle amplifier called a Micro-Channel Plate (MCP) is placed in front of the fluorescent screen, and the ions are passed through the MCP, then observed as a bright spot on the fluorescent screen.



Figure 1 (a) Schematic diagram of the FIM principle, (b) actual FIM observation device, and (c) FIM image of a tungsten needle.

The imaging gas atoms accelerated by the electric field collide with the MCP with a magnification M represented by equation (2).

$$M = \frac{kD}{r} \tag{2}$$

Where D is the distance between the sample and the MCP, r is the radius of curvature, and k is a correction term. In the case of a needle-shaped sample with a radius of curvature of 50 nm, an electric field of about 5×10^{10} V/m is applied to the sample surface when a voltage of 5 kV is applied, and when D is 10 cm, the magnification is about 2×10^6 times (2 million times). Since FIM does not use any lenses, it is not affected by aberrations or vibrations. This phenomenon is known as "field ionization". When a higher voltage is applied to the needle sample, a phenomenon called "field evaporation" occurs. This phenomenon is the ionization of the atoms on the sample surface itself. The 3DAP method, which will be explained next, records the positions (x, y) of atoms that are ionized and ejected from the sample surface under this field evaporation phenomenon using a two-dimensional detector, and identifies the type of atom based on the time of flight (TOF) from when it leaves the surface until it is observed ¹⁾⁻⁵⁾.

2.2 Principles of 3DAP method

3DAPs can be roughly classified into "voltage pulse type" and "laser pulse type," and Figure 2 shows a schematic diagram of a laser pulse assisted 3DAP³⁾. The difference between the "voltage pulse type" and the "laser pulse type" is whether voltage pulses or laser pulses are used to trigger the ionization (field evaporation) of atoms. A high voltage lower than the threshold for field evaporation is applied so that field evaporation occurs at the instant the pulse is applied, and the time of flight of the ions is measured. Since the ions are detected by the projection from the needle sample onto the detector surface, the projection magnification is about 2 million times as described in equation (2), and the position resolution is sub-nm. By continuously inducing field evaporation, which ionizes atoms one by one from the sample surface, the order in which they are detected is recognized as position information (z), making it possible to analyze the positions and types of atoms in three dimensions. The type of atom can be identified by the time of flight as follows: In the kinetic energy equation of Newtonian mechanics $\frac{1}{2}mv^2$, the mass of the moving substance *m* is the mass of the atom (ion), and the velocity v can be calculated from the time of flight t and the flight distance D (the distance between the needle-shaped sample and the detector). If e is the charge of the ion, n is its valence, and V is the potential at the time of ionization, then the kinetic energy is given by

$$\frac{1}{2}mv^2 = enV. \tag{3}$$

Therefore, the mass-to-charge ratio is

$$\frac{m}{n} = 2eV\left(\frac{t}{D}\right)^2.$$
 (4)

This allows us to identify the type of $atoms^{1-5}$.



Figure 2 Schematic diagram of laser pulse-assisted 3DAP.

2.3 Expanding the scope of applications of the 3DAP method

Until about 20 years ago, voltage pulse type 3DAP systems were the mainstream, however the voltage pulse type had several problems. In the voltage pulse type, nanosecond voltage pulses are applied to a needle sample in an electrostatic field to ionize atoms by field evaporation, which requires the sample to be conductive, so the analysis was mainly limited to metallic materials. Furthermore, it is not generally known that frequent sample fracture during 3DAP measurements is a common problem among 3DAP researchers, even for metallic materials. Sample destruction is believed to be caused by electric field stress, and the issue of sample destruction during 3DAP analysis has led to problems with conductive material systems, such as "not being able to obtain the desired 3D atomic map" and "only being able to obtain data from a very limited area". This led to the devising of 3DAP, which induces field evaporation using a laser pulse. 3DAP research groups around the world have been working on the development, and a research group at the National Institute for Materials Science (NIMS) was the first in the world to succeed in the 3DAP analysis of bulk insulators by shortening the wavelength of an infrared femtosecond laser to the ultraviolet (UV) range in their proprietary 3DAP (Figure 3)⁹⁾. At roughly the same time,

the University of Rouen also succeeded in analyzing bulk insulators using a UV laser pulsed 3DAP. Since then, the materials targeted by 3DAP analysis have rapidly expanded to include not only metal materials but also semiconductors and insulators. 3DAP is the only analytical method that can identify and determine the location of all elements, including light elements, and has a high detection sensitivity, so in recent years it has become a powerful and a unique tool not only in materials development, but also in a wide range of fields such as geology, mineralogy and biology^{3),10)}.

2.4 Establishment of 3DAP sample preparation technique by FIB-SEM

The advent of the laser pulse type has dramatically expanded the range of applications for 3DAP. For the preparation of needle-shaped samples from arbitrary areas such as semiconductors, insulators, devices, grain boundaries, and different phase interfaces, microfabrication technology using a Focused Ion Beam (FIB) and needle-shaped sample preparation technology using a FIB-SEM combined with SEM, which became commercially available around 2000, are also major factors that have greatly expanded the scope of 3DAP analysis^{4), 5), 10)}. Conventionally, needle-shaped samples for 3DAP analysis have been prepared using mechanical polishing and electrolytic polishing, however the sample preparation requires a huge amount of time and concentration, and the success rate is not particularly high. As shown in Figure 4, 3DAP specimens are prepared using FIB-SEM by first depositing a protective film on the target specimen using Chemical Vapor Deposition (CVD), and then removing the periphery by milling. The micromanipulator installed in the vacuum chamber of the FIB-SEM is used to lift out the sample, to place it on a support pillar, and then to process it into a needle shape with a tip curvature radius of about 50 nm by annular FIB milling. Since FIB-SEM allows FIB milling while observing with the SEM, it is easy to prepare samples from any area, and the throughput of the sample preparation itself has also improved dramatically.



Figure 3 Laser pulse-assisted 3DAP developed independently by the National Institute for Materials Science (NIMS).



Figure 4 Procedure for preparing 3DAP samples using FIB-SEM (all SEM images are during FIB processing).

2.5 Complementary TEM/3DAP analysis techniques

As mentioned in the previous section, the scope of application of 3DAP is expanding. However, it is difficult to identify the crystal structure or the defect type due to the limited analytical area, the detection efficiency (the ratio of atoms that can be detected among all ionized atoms) of being about 80 % at most, and the constraints of the spatial resolution. Therefore, by performing analysis using TEM and 3DAP in a complementary manner, such as identifying the crystal structure and the defect type by TEM and clarifying the three-dimensional distribution of trace additive elements by 3DAP, a precise nanostructure analysis becomes possible^{12), 13)}. It is important to fully understand the limitations of the 3DAP method and to perform structure analysis on a wide scale using other methods such as TEM and SEM.

3. DOPANT ANALYSIS in COMPOUND SEMICONDUCTOR

3.1 The role of 3DAP in semiconductor dopant analysis

A commonly used technique for evaluating dopants in semiconductors is Dynamic Secondary Ion Mass Spectrometry (D-SIMS). D-SIMS is a surface analysis method that evaluates the element distribution from the surface of a sample to its interior (depth direction) by continuously irradiating the surface of the sample with primary ions and intermittently mass-separating and detecting the secondary ions released by the sputtering phenomenon. The detection sensitivity of D-SIMS is extremely high. Depending on the combination of the matrix and the dopant, it is possible to evaluate dopant concentrations up to approximately 1014 cm-3, making it an indispensable analytical method in the development of semiconductor devices. D-SIMS is mainly used for depth profiling and is suitable for evaluating the dopant distribution in the depth direction of thin films. Although it is capable of measuring two-dimensional distributions on the scale of several microns to several hundred microns, it is difficult to evaluate two-dimensional distributions on the nanoscale.

In semiconductors, activated dopants form potential differences and electric fields at p-n junctions, etc. These potential differences and electric fields can be analyzed at the nanoscale using various TEM techniques. For example, in electron holography, the phase difference of transmitted electrons corresponds to the potential difference¹⁴⁾, and in Differential Phase Contrast Scanning Transmission Electron Microscopy (DPC-STEM), the deflection of transmitted electrons corresponds to the strength of the electric field¹⁵⁾. However, it is difficult to identify the dopant species.

In actual device evaluation, in addition to the evaluation of electric potential and electric field by electron holography and TEM such as DPC-STEM, a method for directly measuring dopants at the nanoscale is desired. Multiple dopants are used in semiconductor devices, and when an unintended electric potential and electric field structure is formed in the device, it is necessary to analyze which dopants are distributed and how they are distributed at the nanoscale. This information is used to optimize the semiconductor manufacturing process and to improve the quality of the device. In light of such analysis needs, 3DAP, which can evaluate dopants with nanoscale spatial resolution, is a promising method. Therefore, in this study, we conducted basic research to analyze dopants in GaAs semiconductors used in semiconductor lasers at the nanoscale.

3.2 Measurement sample

A model sample of compound semiconductor was prepared and a dopant analysis was performed. A GaAs p-n junction was prepared and the dopant concentration was changed in the p and n regions. The range of change was from 10¹⁵ cm⁻³ to 10¹⁹ cm⁻³, with changes in dopant concentration set at one order of magnitude every 200 nm. The dopants used were Si for the n region and Zn for the p region. The structure and SIMS results of the model specimen are shown in Figure 5. This sample was used for potential and electric field analysis studies using vari-



Figure 5 (a) Schematic diagram of GaAs model sample, (b) SIMS dopant profiles of Zn and Si.

ous TEM techniques. The specimens were distributed to many research institutes for basic research into p-n junction analysis using electron holography¹⁴, Lorentz microscopy¹⁴, DPC-STEM¹⁵, diffraction microscopy¹⁶, the Shadow method¹⁷, and electron ptychography¹⁸, and were utilized for the development of electron microscopy.

3.3 Dopant analysis results by 3DAP

The 3DAP device used was a Cameca LEAP5000XS, which can perform measurements with high spatial resolution and high detection efficiency. The pulsed laser used to assist the evaporation was an ultraviolet light with a wavelength of 355 nm. The laser power was 1 pJ. The needle-shaped samples for 3DAP measurement were prepared using a FIB.

A Ga ion beam with an accelerating voltage of 16 kV was used to prepare the needle-shaped samples, and a 2 kV ion beam was used for final cleaning. The FIB used was a FEI HeliosG4UX. Figure 6 (a) shows the atomic map of Zn. The measurement area includes the p-n junction and the 10^{19} cm⁻³, 10^{18} cm⁻³, and 10^{17} cm⁻³ regions of Zn. In this figure, it can be seen that the atomic concen-

trations are different in the 10¹⁹ cm⁻³ and 10¹⁸ cm⁻³ regions. Zn is segregated near the p-n junction. On the other hand, the interface between the 10¹⁸ cm⁻³ region and the 10¹⁷ cm⁻³ region was not clear. Figure 6 (b) shows the Zn dopant concentration profile corresponding to Figure 6 (a). This profile also shows that the Zn concentration is locally high near the p-n junction. In addition, a change in dopant concentration was observed at the interface between the 10¹⁹ cm⁻³ and 10¹⁸ cm⁻³ regions. On the other hand, the concentration change at the interface between the 10¹⁸ cm⁻³ and 10¹⁷ cm⁻³ regions was slight and not clear with respect to the noise. Figure 6 (c) shows the mass spectra obtained from each region. The peaks indicated by the arrows in the figure are Zn peaks. The Zn peak was clear in the 10¹⁹ cm⁻³ region, while it was small in the 10¹⁸ cm⁻³ region and could not be confirmed in the 10¹⁷ cm⁻³ region. These results indicate that the profile in the 10¹⁷ cm⁻³ region in Figure 6 (b) corresponds to the background, and that it is difficult to detect Zn dopants in GaAs less than 10¹⁸ cm⁻³ under these measurement conditions.



Figure 6 Zn dopant analysis by 3DAP (a) Zn atom map, (b) Zn dopant concentration profile, (c) mass spectrum obtained from each region.

Figure 7 (a) shows the 3DAP result with Zn and Si atomic maps superimposed, and Figure 7 (b) shows the dopant concentration profile created in the direction indicated by the arrow in Figure 7 (a). From these results, it can be understood that the Zn and Si dopants are locally concentrated near the p-n junction. Thus, if the dopant concentration is higher than 10¹⁸ cm⁻³, it is possible to analyze the local dopant maldistribution. This uneven distribution of dopants was not intended in the design of this model sample.

In actual semiconductor devices, such unintended uneven distribution of dopants can occur. In such cases, if the local structure of the dopants is analyzed in three dimensions using 3DAP, it is possible to confirm whether the device is fabricated as designed, and this can be used for failure analysis of semiconductor devices.



Figure 7 Zn and Si dopant distribution near the p-n junction (a) Zn and Si atom map, (b) Zn and Si dopant concentration profile.

4. COPPER ALLOY¹⁹⁾⁻²²⁾

4.1 Measurement sample

The measured specimen was a Cu-Ni-Si alloy containing 2.5 mass% Ni and 0.6 mass% Si. The Cu-Ni-Si alloy was melted and cast, then heat treated, rolled, annealed, and then solution treated. After that, aging precipitation heat treatment was performed. 3DAP measurements were performed on Cu-Ni-Si alloy specimens aged at 425 °C, 450 °C, 500 °C, and 550 °C. The aging time was 2 hours.

4.2 TEM observation

For TEM observation, a JEM-2100plus from JEOL was used. For STEM observation, a JEM-ARM200F from JEOL was used. The electron beam acceleration voltage was 200 kV. For STEM observation, High-Angle Annular Dark Field (HAADF) STEM images were taken.

Figure 8 shows a bright-field TEM image of the Ni-Si precipitates in a Cu-Ni-Si alloy that had been subjected to aging precipitation heat treatment at 550 °C. Numerous precipitates approximately 10 nm in size are observed in the left region of the TEM image. Contrast due to strain is observed in the copper matrix surrounding the precipitates. In addition, a phase approximately 100 nm in size is observed in the right region of the TEM image. Since this phase was also observed in the solution-treated sample, it is a phase that existed before the aging precipitation heat treatment.

Next, Figure 9 (a) shows a magnified HAADF-STEM image of one of the precipitates, which is approximately 10 nm in size. The electron beam was incident on Cu at [110]. Figure 9(b) shows the two-dimensional Fast Fourier Transform (FFT) pattern from the frame in Figure 9 (a). In the FFT pattern, in addition to the diffraction points from

the copper matrix, the diffraction points from δNi_2Si were also confirmed. From this electron beam diffraction pattern, it can be seen that the basal plane of δNi_2Si is the (100) crystal plane, and this basal plane is in contact with the (110) crystal plane of Cu.



Figure 8 Bright-field TEM image of 550 °C heat-treated copper alloy.



Figure 9 (a) HAADF-STEM image of δNi₂Si precipitate, (b) FFT pattern of copper alloy.



Figure 10 3DAP results for heat treated samples at aging temperatures of 425, 450, 500 and 550 °C.



Figure 11 3-D atom probe tomographic reconstruction of 500-degree heat treated copper alloy.

4.3 Analysis of copper alloys using 3DAP

The 3DAP measurement results are shown in Figure 10. The 3DAP device used was the EIKOS-UV from Cameca. EIKOS-UV is a popular version of the device with basic performance, and the device used was installed at the NIMS-CAMECA 3DAP Laboratory. The pulsed laser used to assist the evaporation uses ultraviolet light with a wavelength of 355 nm. Each figure shows the results for the samples heat-treated at aging temperatures of 425, 450, 500, and 550 °C. The 2.5 atomic% Si isoconcentration plane and the Cu atomic map are displayed. It can be seen that the precipitates coarsen as the aging temperature increases. The precipitates in the samples heattreated at 425 and 450 °C are close to spherical, while the precipitates in the samples heat-treated at 500 and 550 °C change to ellipsoids. Thus, the analysis with 3DAP makes it possible to visually grasp the size and shape of the precipitates in three dimensions.

The results of the 3DAP analysis of the 500 °C aged sample with an expanded measurement range are shown in Figure 11. The figure shows the isoconcentration surface of 4 atomic% Si. The measurement took almost one day, and a field of view range of about 1 μ m was obtained. Approximately 1,000 precipitates were measured, and sufficient statistics were obtained. By using ultraviolet laser pulses, it became possible to stably obtain data from a wide area even from copper alloys. In the results, most of the precipitates were several nm to 10 nm in size, while phases of about 50 nm were also confirmed. These were coarse phases that had existed before the aging precipitation heat treatment, which were also observed in the TEM images.

Next, in order to analyze the precipitates in detail, we used the LEAP5000XS, which is equipped with a more

advanced detector than the EIKOS-UV and therefore has a higher detection efficiency. The 3DAP results of the 550 °C aged sample are shown in Figure 12. Here, the isoconcentration surfaces of 14 atomic% Ni and 7 atomic% Si are shown. From this view, the distribution of Ni and Si was almost the same, and the precipitates were not spherical but had an ellipsoidal plate shape close to a disk. In order to analyze the detailed composition within the precipitated phase, a 3DAP analysis of a single precipitate is shown in Figure 13. Figure 13 (a) shows the isoconcentration surface of 7 atomic% Si. The concentration profile of the precipitate created in the direction indicated by the arrow in the figure is shown in Fig. 13 (b). Since the ratio of Ni to Si is 2:1 in the center, the precipitate phase is found to be Ni2Si. This result is consistent with the result that the precipitate phase was Ni2Si from the analysis of the electron beam diffraction



Figure 12 3D atom map obtained by APT (iso-concentrationsurfaces of Ni at 14 at% and Si at 7 at%).

pattern shown in Figure 9 (b). It can also be seen that Ni, Si, and Cu diffuse into each other at the interface between the precipitates and the copper matrix. A closer look at the diffused region reveals two distinct features. The first is the region indicated by arrow 1, where the Si composition is constant and the Ni composition decreases toward the copper matrix. This region is considered to be $\delta(N_{1-y}, Cu_y)_2$ Si, as suggested by Yi et al.²³⁾. The other region is indicated by arrow 2, where Ni and Si diffuse into the Cu matrix at a ratio of less than 10 %. Figure 14 shows a model diagram of these precipitates estimated from the 3DAP. Thus, the 3DAP makes it possible to visualize the three-dimensional structure of the precipitates and to analyze it in detail.



Figure 13 Si 3DAP map of single precipitate (iso-concentration-surfaces of Si at 7 at%) and composition profiles obtained by 3DAP.



Figure 14 Core-shell model of precipitate in copper alloy.

Finally, the frequency distribution of the volume of precipitates was analyzed from these 3DAP results. From the 425 °C aged sample, 39 precipitates were analyzed in three 3DAP samples, from the 450 °C aged sample, 345 precipitates were analyzed in two 3DAP samples, from the 500 °C aged sample, 1137 precipitates were analyzed in five 3DAP samples, and from the 550 °C aged sample, 30 precipitates were analyzed in three 3DAP samples. Figure 15 shows the relative frequency distribution of the precipitate volume for each sample. Here, the volume of the precipitate was defined as the 2 atomic% isoconcentration plane of Si. From this frequency distribution, it can be seen that the precipitate coarsens as the aging heat treatment temperature increases. The average volume of the precipitate was 6.7 nm³ for the 425 °C aged sample, 29.9 nm³ for the 450 °C aged sample, 446 nm³ for the 500 °C aged sample, and 1328 $\rm nm^3$ for the 550 °C aged sample. In addition, the average radius of each precipitate was calculated. Considering the shapes of the precipitates shown in Figure 10, it was assumed that the precipitates in the 425 °C and 450 °C aged samples were spherical, the precipitates in the 500 °C aged sample were spheroids with an axial ratio of 0.6, and the precipitates in the 550 °C aged sample were spheroids with an axial ratio of 0.3. As a result, the average radii of the precipitates in the 425 °C and 450 °C aged samples were 1.2 nm and 1.9 nm, respectively, and the average major radii of the precipitates in the 500 °C and 550 °C aged samples were 5.6 nm and 10.2 nm, respectively. By acquiring 3DAP data over such a wide measurement range, it is possible to obtain average information that is useful for understanding the material properties.



Figure 15 Relative frequency of precipitate volume.

5. CONCLUSION

In this paper, we have shown that 3DAP is effective for analyzing nanoscale structures such as dopants in semiconductors and precipitates in copper alloys. If used appropriately, 3DAP can analyze semiconductor devices and various materials, providing detailed insight into various products. By utilizing the analysis results in the next design and manufacturing optimization, it can contribute to improving the reliability and the characteristics of new products.

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