Introduction

The JEBG-3000UB High Power Electron Beam Source produces a high-power electron beam with a maximum beam output of 300 kW, thus the JEBG-3000UB is used for melting and purifying metal materials. In this paper, an example of applying the JEBG-3000UB High Power Electron Beam Source to the production process of polycrystalline Si, and the features of the JEBG-3000UB are described.

Solar Cell

Photovoltaic power generation has been drawing much attention as clean, recyclable energy, and various materials are studied for this power generation. These materials are divided roughly into three categories, silicon, compound semiconductor and organic material. Table 1 shows conversion efficiencies for each category and their features [1].

The solar cell using crystalline Si has a high conversion efficiency of 13 to 18%, and also has a long service life of 30 years. Thus, the solar cell dominates about 80% of the total production of photovoltaic power generation. It is predicted that the production of solar cells will rise with a high annual increase rate of 30 to 40%. However, polycrystalline Si materials fall short of this expected production increase. Thus, a major key factor that we are encountering is whether we can supply enough polycrystalline Si materials to satisfy the production needs of solar cells.

Supply of Polycrystalline Si Materials

The production capacity of polycrystalline Si materials in the world, including those for semiconductors, is about 40,000 tons per year. This worldwide production capacity is predicted to be more than 100,000 tons in 2010, as shown in Fig. 1 [2], [3]. It should be noted that the production capacity in 2007 and subsequent years is an estimate that totals production increases announced in the production plans of semiconductor material companies.

Although a high purity of eleven nines (99.999999999%) is required for Si materials for the semiconductor industry, as for Si materials for the solar cell, a purity of six nines (99.9999%) is enough.

As typical production methods of polycrystalline Si materials, the Siemens method and the melted Si purification method are described.

Siemens method

This method first vaporizes Si metal (purity: 99%) to generate trichlorosilane (SiCl₃), and finally purifies Si. Then, the Si is solidified again [4-6]. The procedure is as follows.

1) Si metal and hydrochloric acid (HCl) are reacted to produce liquid trichlorosilane (SiCl₃).
2) Distillation and purification of trichlorosilane are repeated to highly purify it.
3) In a deposition chamber (Fig. 2), a Si rod is heated to about 1000 °C. By passing trichlorosilane (SiCl₃) and hydrogen through the chamber, high-purity polycrystalline Si is deposited on a Si rod. As a result, Si with a high purity of eleven nines is obtained.

Melted Si purification method

The melted Si purification method developed by the NEDO project is described [6], [7]. In this method, Si metal (purity: 99%) is used as a starting material. While Si is kept in the solid phase, impurity elements contained in the Si are removed and Si for solar cells is produced. Si with a purity of six nines is obtained. Although the purity of the Si is low compared with the purity obtained by the Siemens method, the melted Si purification method has several advantages. That is, the energy needed to produce Si is very low, and the capital investment for the production of Si materials can be held down to a low level.

To be more precise, the melted Si purification method consists of the first process and the second process. The first process includes phosphorous (P) removal and rough removal of metal impurities, and the second process
Table 1 Conversion efficiencies and features of various solar cells.

<table>
<thead>
<tr>
<th>Typical category</th>
<th>Power generation efficiency (%)</th>
<th>Main features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon system</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polycrystal type</td>
<td>13 - 17</td>
<td>For mass production</td>
</tr>
<tr>
<td>Single-crystal type</td>
<td>16 - 18</td>
<td>High conversion efficiency</td>
</tr>
<tr>
<td>Ribbon</td>
<td>16</td>
<td>Slice process not required</td>
</tr>
<tr>
<td>Thin film type</td>
<td>7 - 12</td>
<td>Deposition with low temperature, large area, and multi-layers is possible.</td>
</tr>
<tr>
<td>Compound semiconductor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single-crystal type (GaAs)</td>
<td>30 - 40</td>
<td>High conversion efficiency</td>
</tr>
<tr>
<td>Polycrystal type (CIGS,CdTe)</td>
<td>13</td>
<td>High cost</td>
</tr>
<tr>
<td>Organic system</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dye-sensitization type</td>
<td>6</td>
<td>Vacuum and high-temperature process not required</td>
</tr>
<tr>
<td>Organic thin film type</td>
<td>4</td>
<td>Low cost is possible.</td>
</tr>
</tbody>
</table>

Fig.1 Production capacity of polycrystalline Si in the world. (Source : RTS Corporation)

Fig.2 Schematic diagram of Siemens method.

Fig.3 Process and schematic diagram of melted Si purification method.
includes boron (B) and carbon (C) removal, and finish removal of metal impurities (Fig. 3).

P removal is performed by the electron beam vacuum-melting method. Si metal is irradiated with a high-power electron beam, and the Si metal is dissolved. Depending on the difference of vapor pressure, P is vaporized preferentially and the purity of Si is raised.

**J EOL 300 kW High Power Electron Beam Source**

The JEBG-3000UB 300 kW High Power Electron Beam Source, developed by JEOL, is used for the purification of polycrystalline Si materials for solar cells by means of the melted Si purification method. Figure 4 shows the appearance of the JEBG-3000UB.

**Specifications**

Table 2 shows the specifications for the JEBG-3000UB [8]. The maximum beam output is 300 kW (at an accelerating voltage of 40 kV and a maximum emission current of 7.5 A).

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum output</td>
<td>300 kW (40 kV, 7.5 A)</td>
</tr>
<tr>
<td>Accelerating voltage</td>
<td>-40 kV</td>
</tr>
<tr>
<td>Electron-beam scan width</td>
<td>+/-500 mm</td>
</tr>
<tr>
<td>Scanning coil</td>
<td>Two axes (X,Y) (X and Y orthogonal)</td>
</tr>
<tr>
<td>Dynamic focusing lens</td>
<td>Option</td>
</tr>
<tr>
<td>Astigmatism correction coil</td>
<td>Option</td>
</tr>
<tr>
<td>Corresponding power supply</td>
<td>JEOL JST-300C</td>
</tr>
</tbody>
</table>

**Structures and features**

Figure 5 shows the electron optical system of the High Power Electron Beam Source. This electron optical system is roughly divided into three systems.

1. The illumination system consisting of a filament, a tungsten (W) cathode, a Wehnelt, and an anode.
2. The imaging system consisting of the 1st lens and the 2nd lens.
3. The scan system consisting of a dynamic focusing lens, an astigmatism correction coil, and an X/Y deflection coil.

The bombardment method is employed for the illumination system. The bombardment method generates thermoelectrons with heating of a filament, heats a disk-shaped W cathode, and then generates an electron beam from the W cathode. This bombardment method is superior to the filament method, in terms of the following three points.

(a) An electron beam with higher current density is obtained.
(b) The emission of electrons from the surface of the cathode makes it possible to more sharply focus the electron beam.
(c) In the filament method, the filament is directly suffers from ion bombardment, thus it is likely to burn out. In the bombardment method, since the cathode is disk-shaped, it can work for long periods of time.

In addition, a grid-assembly construction of the filament and W cathode leads to one unit focusing system containing insulating oil.

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**Fig.4 Appearance of JEBG-3000UB High Power Electron Beam Source.**

**Fig.5 Electron optical system of High Power Electron Beam Source.**
geometry, thus simplifying the positioning and maintenance of the illumination system.

The imaging system has a function to focus the electron beam onto the surface of a material, by means of two lenses of the 1st lens and the 2nd lens.

The scan system performs electron beam scan by means of the X/Y deflection coil. In addition, a dynamic focusing lens and an astigmatism correction coil have functions which respectively correct a focus shift and the shape of the electron beam, during the beam scanning.

Furthermore, the JEBG-3000UB has various scan control parameters to effectively operate as a high power electron beam source. Figure 6 shows these parameters, including the control parameters for the amplitudes in the X direction (XA), those for the amplitudes in the Y direction (YA), those for rotations in the X and Y directions (X-ROT, Y-ROT), those for dwell time (DT), and those for the beam shape.

**Figure 7** shows examples of various scans performed by the JEBG-3000UB, presenting line scan, X-ROT added to line scan, and YA added to line scan. The JEBG-3000UB enables such a variety of scans, making it possible to uniformly dissolve surfaces of materials.

**Figure 8** presents the image of applications of the JEBG-3000UB High Power Electron Beam Source to purification of polycrystalline Si materials (P removal).

**Conclusion**

As described above, the JEBG-3000UB has various features suitable for the production of polycrystalline Si materials. By exploiting these features, it is expected that the JEBG-3000UB will contribute to expanding the applications of solar cells.

**References**