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Development Trend for High Purity Silicon Raw Material Technologies
— Expecting Innovative Silicon Manufacturing Processes for Solar Cell Applications —

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1 Introduction

Solar energy is potentially capable of supplying most of the global need for primary energy, and it is expected to become an alternative source for fossil fuels as a clean energy, but the economic aspect of the system is a major hindrance to its growth. Yet, as accessible fossil fuels will run out in time as well as a growing global emphasis for introducing systems to reduce environmental burden[1], solar power generation is gaining importance every year. For the past 10 years, annual worldwide production of solar cell systems has been growing 30 to 35%. In terms of solar power generation, it reached about 1.7GW in 2005[2]. As a result, there is a shortage of high purity silicon raw materials. Future use of solar cell systems is expected to increase at a rate higher than in the past[3].

Presently, solar power energy is many times more expensive than that of fossil fuels. Every year, the cost of the solar cell portion for installation is increasing[4], and hence the reduction of its cost share, more than 50% now, is indispensable for expanding solar energy use. A share of the cost of silicon in the cell is estimated to be about 20%, making it an important factor for minimizing cost increase stemming from a shortage of raw materials.

As indicated in "The Third Science and Technology Basic Plan," projects for research and development in the field of nanotechnology and materials will develop innovative materials, dramatically improving power conversion efficiency and enabling high efficiency energy utilization. In order to develop commercial processing technologies, it is proposed that the technologies enabling nanoscale control need to be established for material morphology, structures, and grain-boundaries[5]. Also, in the field of nano-electronics, it has been stated that for the next 10 years, silicon-based semiconductor device technologies should realize further high functionalities, a key to fast advancing an information-oriented society .

In this article, we review the background and development trends of solar cell grade silicon, and discuss the current status for high purity silicon supply and its processing technologies. Also, as strategies for coping with the silicon shortage, we review current developments of raw materials processing technologies, and discuss expected emerging materials science analyses or potential innovative process technology developments. In concluding, we would like to propose promotional organizations for addressing the silicon shortage.

2 Reasons for attention given to polycrystalline silicon solar cell

2-1 Rapid expansion of solar power generation

Lead by Europe, with a strong conviction for environmental issues, deployment of solar power generation is fast advancing worldwide[1,6,7]. The United States seems to take an interest in solar power generation more from the standpoint of energy security. The global power generated by solar cell systems reached 1.2GW in 2004 and 1.7GW (forecasted) in 2005. In terms of penetration rate, Germany is at the top in the world. This is because in Germany, the “Renewable Energy Sources Act” and “100,000 Roof Scheme” created the solar power boom prompted by setting up a subsidy program to purchase (solar power) electricity, which is 3 to 4 times higher than that of a traditional one[1,8].

The total world solar cell system production in 2004 was nearly 60% higher than the previous year, a significant growth. In terms of each country’s system production, Japan generated 0.6GW, Europe 0.3GW, and the U.S. 0.14GW, demonstrating remarkable growth in Japan and Europe[9]. According to the report “Renewable Energy Scenario to 2040” by the European Renewable Energy Council, the prediction is that solar power’s share of total world electric power will be 0.1% in 2010, 1.1% in 2020, and 8.3% in 2030[3].

Figure 1, prepared by the New Energy and Industrial Technology Development Organization (NEDO), shows the world production of solar cell modules, future forecasts, and a road map for solar power generation from the cost point of view[2,10,11]. Assumed here is that the cumulative deployment of solar power until 2030 is 100GW, which is 10% of the total power.

About 95% of the current solar cell module market is based on solar cells using silicon as raw material, of which about 60% is polycrystalline silicon, called bulk crystalline silicon, and 30% is single crystal silicon[9,12]. For the past 3 years, these figures have remained about the same, which is expected to continue for some time.

For further expansion of solar power system, it is necessary to lower the cost of solar cell module, comprising 60% of the system cost. To this end, the challenge is to reduce the cost of silicon raw

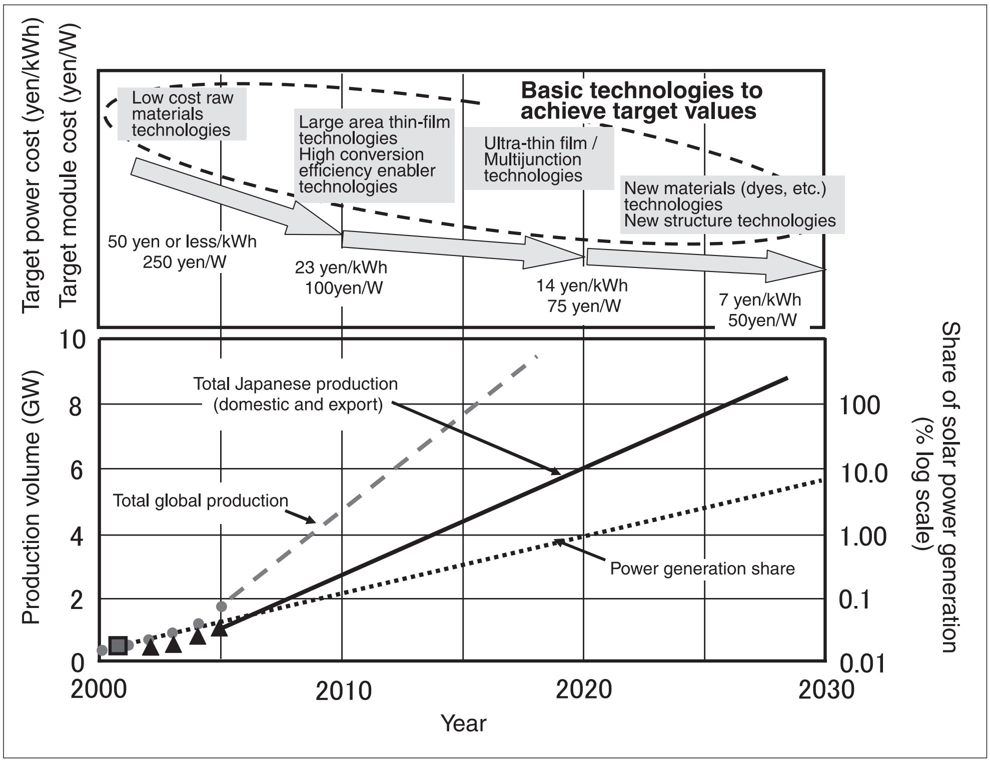


Figure 1 : World production of solar cell modules, future forecasts, and a road map for solar power generation from a cost point of view

Reproduced by the STFC based on References[2,10,11] by New Energy and Industrial Technology Development Organization (NEDO) materials, which comprise 20% of the module cost. Technology development realizing a vast cost reduction of module production is crucial, and equally so is the stable supply of silicon raw materials. However, if the current trend continues, the fear is that the silicon shortage will put a limit on solar power growth — it goes without saying that the cost reduction efforts for silicon raw materials will be overshadowed.

2-2 Issues for each type of solar cell by materials and its power generation efficiency

In terms of materials, solar cells are broadly classified into silicon system, compound semiconductor system, and organic system. Table 1 lists conversion efficiencies of solar cell modules, major features/issues, and summaries of the current status for each technology[9,10,13].

(1) Bulk type silicon system

In terms of crystalline states or device structures, silicon solar cells are classified into four types: bulk, thin film, single crystal, and polycrystalline. Among the types, bulk type silicon solar cell has the major share of current production, and this trend is expected to continue for some time. Power conversion efficiency is 16 to 18% for single crystal and 13 to 17% for polycrystalline.

Solar cell silicon, despite high purity, is orders of magnitude lower in purity than the semiconductor grade silicon, thus traditionally sourcing the off-grade silicon from the semiconductor industry. However, because solar cells require greater volume of silicon when compared with semiconductor chips, more silicon is produced just for the solar cell application in order to meet recent rapid increase in demand. With such high demand, development for low cost raw materials manufacturing is drawing attention. In particular, for bulk type solar cells of high silicon consumption, under development are technologies to reduce the crystal thickness (down to 50μm from 100μm) and cutting waste during the slicing process to lower material consumption, helping save raw materials.

(2) Thin film type silicon system

A thin film type solar cell is the one in which thin film silicon is deposited on a substrate. Since the raw material requirement is small, it is considered as a low cost solar cell for future mass production. However, even if thin film of crystalline silicon is formed, its power conversion efficiency is much lower than that of bulk type silicon. When thin film is amorphous, the power conversion efficiency gets even lower,

Table 1 : Conversion efficiencies of solar cell modules and major features/issues

Representative type			Production volume (2003)	Power conversion efficiency (module, %) Current	Target in 2030 (NEDO)	Major features and issues
Silicon system	Bulk type	Polycrystalline	61	13~17	22	• Established record for mass production
		Single crystal	27	16~18	—	• High conversion efficiency
		Ribbon	1	16	—	• Slicing step not needed
	Thin film type (amorphous, crystalline)		4	7~12	—	• Possibility for low temperature, large area, and multilayer manufacturing • Low cost potential
Compound semi-conductor system	Single crystal type (GaAs system)		—	30~40	—	• High conversion efficiency, but high cost • Containing environmental burden substances
	Polycrystalline type (CIGS, CdTe)		1	13	18	• Necessary to secure In sources, reduce consumption, and explore alternatives to In • Necessary to improve the system reliability
Organic system	Dye-sensitized type		—	6	15	• No need for vacuum and high temperature processing • Low cost potential • R & D stage
	Organic thin film type		—	4	—	

* Ribbon means a thin film product manufactured directly from a silicon melt utilizing its surface tension (string-ribbon method), about 100nm to a few hundred μm in thickness.

Reproduced by the STFC based on References[9,10,13]

7 to 10%, despite the advantage that formation at low temperature enables greater varieties of substrates to choose from. Accordingly, improving power conversion efficiency is a key to reduce the power generation cost with these solar cells. As its power conversion efficiency improves, it is likely to become a mainstream technology because of its merit, that is, low raw material consumption.

(3) Compound semiconductor and organic systems

Compound semiconductor and organic systems are expected to become the next-generation solar cells. Research and development are taking place and the part of them has already been put into practical use. However, it is unlikely that they will replace a silicon system as the major alternative in the near future.

Since the expectation is that the compound semiconductors are theoretically capable of yielding higher efficiency than silicon, research and development are continuing. For instance, a polycrystalline thin film of a compound thin film type solar cell, CIGS (Cu-In-Ga-Se), has achieved power conversion efficiency exceeding 13%, and its band gap can be altered in accordance with its composition, which is considered as a merit. However, since indium(In) is in short supply, the supply and the cost problems are basically irresolvable. GaAs compound thin film type solar cells are also used but there is a concern along with the supply of raw materials that a large consumption of arsenic (As) will have environmental problems in the future. Although these compound semiconductor type solar cells are now increasing in production, eventually they will be targeted only for specialty applications.

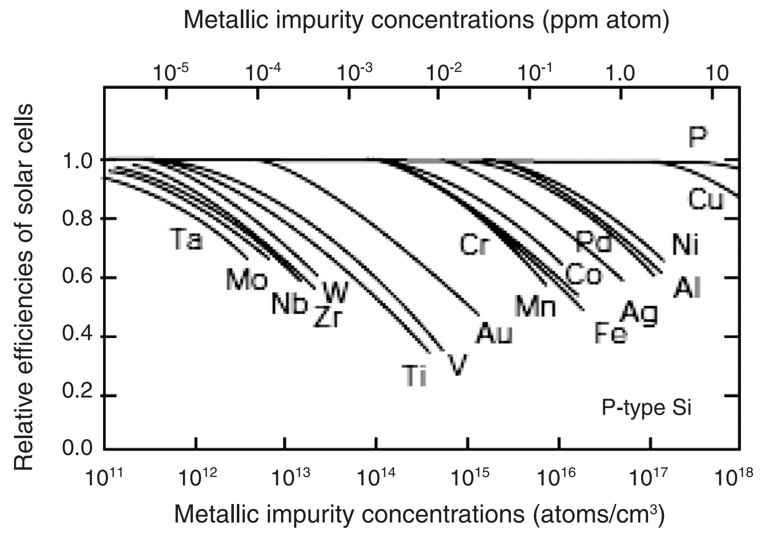
The organic systems, being overwhelmingly low cost in raw materials, may not be applicable for high efficiency power generation, but expected in applications for a low cost and/or a wearable solar cell. Organic dye-sensitized solar cells are reported to demonstrate greater than 10% in power conversion efficiency, providing high hopes for future low cost solar cells. However, up to now, they are not commercialized because of issues such as outdoor module efficiency, stability, life-expectancy, and reliability.

The quantum dot solar cell, not based on single junction, can potentially produce significantly high theoretical efficiency of 60%, drawing much attention from nanotechnology field. However, research in this field has just begun.

2-3 Relationship between power generation and impurity concentration in silicon system solar cells

Silicon for solar cells (99.99999% pure) is low in purity compared with that for semiconductors (99.999999999%), but the power conversion efficiency of solar cells is largely dependent on impurity levels in the silicon raw materials. Therefore, it is necessary to determine what the allowable impurity levels are in regard to both power conversion efficiency and associated costs. Currently, the guidelines for allowable impurity levels in silicon materials vary in accordance with the material suppliers due to existing relationships with the cell and module preparation processes.

Figure 2 shows impurities influencing the single crystal silicon solar cell performance and their concentrations found in various silicon raw materials[14-16]. Since many metallic impurities, present in less than the order of ppm, such as iron, aluminum, titanium, and others affect acutely the power performance, it is necessary to understand their quantity limits. The impurities are thought to delicately interact with grain boundaries and crystal defects, affecting the electric characteristics. However, full elucidation has not been conducted on the effect of impurity behavior in grain boundaries and crystals on cells characteristics[17]. It should be necessary to clarify these issues if low cost and high efficiency silicon system solar cells are to be realized.



(Unit : mass ppm)

	B	P	Fe	Al	Ti	C	O
Industrial metallic Si	5-10	25-30	1000-1500	600-800	150-200	150-200	–
Remelting Si for solar cells	0.1-0.3	<0.1	<0.1	<0.1	<0.1	<5	<6
Substrate Si for solar cells	0.1-0.3	<0.1	<0.007	<0.06	$<4\times10^{-5}$	<3	<4

Figure 2 : Impurities influencing the single crystal silicon solar cell performance and their concentrations found in various silicon raw materials

Copied from References[14-16]

3 Forecasted demand for high purity silicon

With the recent significant growth of solar cell production, the demand for high purity silicon as a principal raw material is rapidly increasing, eliciting a shortage of high purity silicon. This is because many raw materials suppliers are prudent in making capital investment now, due to the fact that when high purity silicon was in short supply for semiconductors, they expanded manufacturing facilities only to find themselves with overcapacity. From a business point of view, the business of silicon system solar cells are comprised of five business sectors: silicon raw materials, ingots, wafers, cells, and modules. The further the downstream in business, the more production capacities are required, creating out of balance situations. Also, compared with downstream operations, upstream requires greater capital investment as well as longer lead times for construction of facilities for the same level of downstream production capacity, all of which are responsible for the current silicon shortage[18].

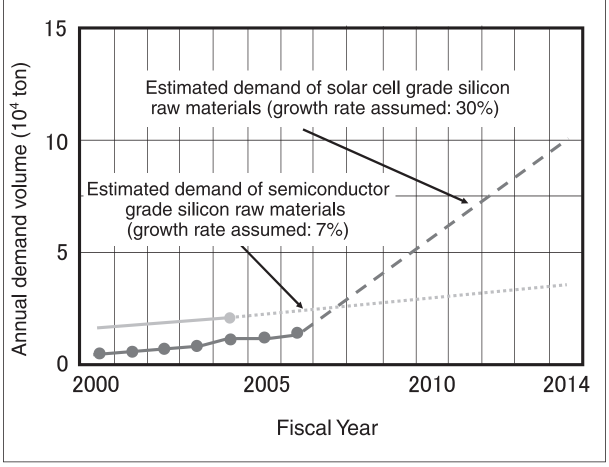


Figure 3 : Predicted total world demand of high purity silicon raw materials

Reproduced by the STFC from References[2,18,19] to calculate annual production volume assuming the growth rates

Figure 3 presents the estimated total worldwide high purity silicon supply[2,18,19]. In this chart, the pre-2005 annual production is based on actual volume (or predicted estimated value), but from 2006 onward, annual production volume is calculated based on the predicted silicon demand growth for solar cells and semiconductors. The average annual growth rate for the near future is predicted at 7% for semiconductor silicon and 30 to 35% for solar cell silicon. According to this chart, in 2007 silicon production for solar cells will exceed that of semiconductors. Currently, there are ten manufacturers of solar grade silicon raw materials in the world (Japan, the United States, and Germany). The top four companies are also wafer suppliers. For the next two or so years, even these ten companies will not be able to meet the raw material supply, thus undoubtedly causing a shortage. Furthermore, for the next several years, total demand for both semiconductor and solar cell applications will probably continue to exceed the total world production capacity of high purity silicon, creating a concern that the silicon shortage will become a stumbling block for solar cell growth.

In several years, the demand and supply balance will probably be stabilized, but the situation of the whole industry may be drastically changed. In the future, while Japan has been a leader in silicon supply for the semiconductor industries, the high purity silicon for semiconductors will be a specialty product in terms of total demand of high purity silicon. In this regard, when solar application becomes a major one, it is uncertain if Japan can continue positioned in a leading role for the silicon industry of solar cell application.

4 Processing technologies of high purity silicon for solar cell application

4-1 Development status of processing technologies for silicon raw materials

Table 2 summarizes the high purity silicon processing technologies for solar cell application, including those under development[19,20]. This chart also shows domestic patent application activities for each processing technology.

Roughly speaking, purification processing technologies are classified into chemical and metallurgical methods. The current mainstream method for raw materials processing is chemical, using repeated refinement of trichlorosilane ($SiCl_3$) (Siemens method). The processing starts with reducing silica sand (silica, SiO_2) making low grade silicon. This silicon reacting to hydrochloric acid yields trichlorosilane, from which impurities are removed via distillation and refinement. Then reacting the refined trichlorosilane with hydrogen at high temperatures yields high purity silicon deposits.

Table 2 : Processing technologies for high purity silicon for solar cell application and the activities in patent application

Basic approach	Features (secondary raw materials)		Production processes	Number of patent applications (1/1996 to 3/2006)	Representative companies	Status of development
Metallurgical approach	• Simple process • Low cost		Molten silicon refinement method	25	JFE Steel Corporation Nippon Steel Corporation Elkem Solar Crystal Systems Dow Corning	• Basic technology established • Large scale technologies under demonstration
Chemical approach	• Complex processes • High purity	$SiHCl_3$	Improved Siemens method	1	Hemlock	
					Wacker	
			VLD method	—	Tokuyama	
			Fluidized bed method	—	Wacker	—
		SiH_4	Fluidized bed method	—	REC	
			Inside silicon tube method		Joint Solar	
		$SiCl_4$	Zinc reduction method	10	Chisso	

* VLD (Vapor to Liquid Deposition) method: Silicon deposition method from silicon solution
The search system of the Japan Patent Office was used to search words, silicon, high purity, and solar cell from 1996 onward, and a total of 65 patent applications were found. Among the metallurgical and chemical approaches, 36 were selected, relating to high purity silicon processing technologies. It should be noted that the names of patent applicants and assignees, i.e., representative companies, do not necessarily agree.
Prepared by the STFC based on References[19,20]

The processes require a significant amount of electricity.

4-2 Trends for measures against silicon raw materials shortage

As illustrated in figure 4, one measure against the shortage of high purity silicon for solar cell application is to make best efforts to increase production capacity by expanding facilities and introducing new manufacturing process technologies because one premise is that the traditional cell technologies will continue to be used for the foreseeable future. At the same time, a long term development project for new cell structures is carried out in order to attain high efficiencies. In terms of policies, two major directions are being pursued: reduction of materials use and increase of raw materials production.

(1) Reduction of silicon use

In the future, more efforts will be focused on lowering as much silicon consumption per unit power as possible, by reassessing materials technologies to improve power conversion efficiency along with using new cell technologies. As mentioned already, in terms of the smaller consumption of silicon, the preference is to use single crystal or thin film silicon, but the cost is high. Still another approach is to make spherical silicon from the molten silicon, which is arranged within the reflector/electrode combination forming new structure cells, enabling significantly reducing silicon[21,22].

Further example showed that power generation was multiplied[23] by developing double-faced solar cells made from single crystals.

In addition, some researchers are attempting to reduce silicon consumption by developing a new machining method achieving lower raw materials waste[18]. More developments to reduce silicon consumption are reported: using fine wires when machining silicon ingot, thinner wafers are made; ribbon type wafers are made directly from molten silicon utilizing its surface tension; and a film-forming method developed for preparing wafers.

(2) Improved raw materials manufacturing processes and new developments, enabling expansion of silicon raw materials production

For improving the Siemens method, a current mainstream production process, the number of refinements is being minimized via increasing trichlorosilane's refinement efficiency, thus increasing the production volume per unit time. Also being pursued is the improvement

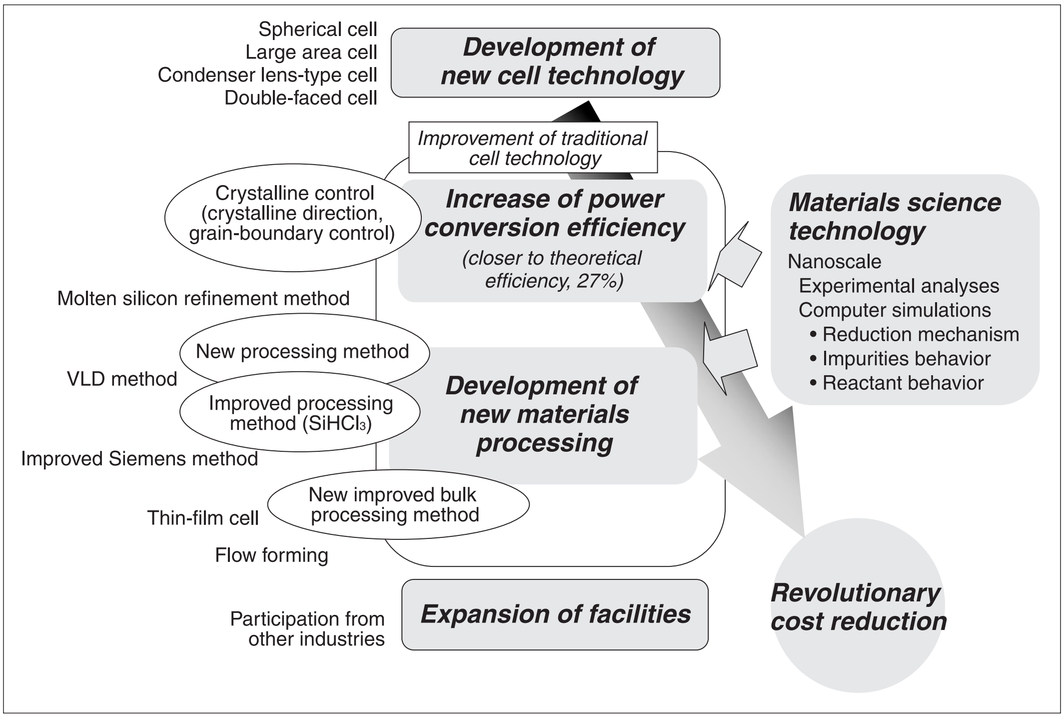


Figure 4 : Measures against polycrystalline silicon raw materials shortage

of ultimate product efficiency for high purity silicon. However, the Siemens method has been used for almost 30 years, during which time the method has undergone many improvements, offering little hope for drastic future improvement of refinement efficiency.

There are some candidates for new processing: VLD (Vapor to Liquid Deposition) and Molten Silicon Refinement methods. In the VLD method, trichlorosilane together with hydrogen is injected into graphite tubing heated at 1,500°C, producing a silicon melt deposit. The deposition rate is faster than that of the traditional Siemens method, enabling high efficiency silicon raw material production[17,19].

In contrast, the molten silicon refinement method uses a metal refining technology, reducing silicon's impurity concentration via metallurgical approach. Although it cannot be used for semiconductor application, solar cell grade is a good option. This has advantages in that different industries may be able to participate and also initial production facilities can be small compared with the chemical approach (approximately 100 tons). With a technology developed by the NEDO project, a metallurgical production processing, the metallic silicon of 99% purity is used as a starting raw material, from which impurity elements are removed to make high purity solar grade silicon. In this method, solidification refinement is performed twice. For the first step, after removing phosphorus with a graphite container under high vacuum, iron, aluminum and titanium are removed in the first solidification refinement. A zone concentrated with impurities in this ingot is cut out; then the remainder is crushed and washed. For the second step, after removing boron and phosphorus by water vapor oxidation in a plasma melting furnace, iron, aluminum, and titanium are again removed by a second solidification refinement[17,20,21].

5 Materials science technologies expected to contribute to making high purity silicon raw materials

Figure 5 presents various nanoscale approaches to elucidate impurity behaviors in silicon, showing potential capabilities. They are illustrated according to intermediate processing products staring from raw materials silica to solar grade silicon (99.99999% purity). As can be seen below, focused efforts of nanoscale experimental analyses and computer simulations are necessary in order to analyze impurity behaviors in crystals and grain boundaries. However, historically in

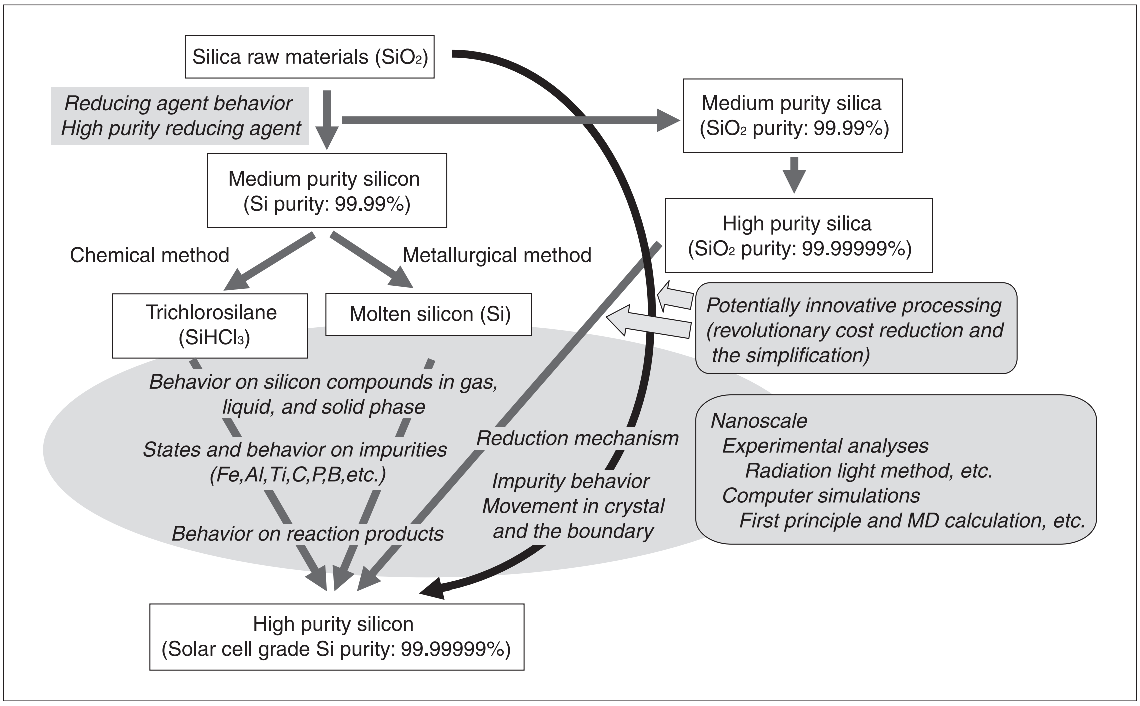


Figure 5 : Nanoscale approaches to analyze behaviors on impurities included in silicon

Japan, the traditional research and development of solar cells is centered around device development and the materials research mostly relies on the semiconductor silicon industries, generating fewer numbers of materials scientists in this field at universities and public institutions.

5-1 Need for analyzing impurity behaviors for high purity production processing

Aiming at the ultimate objective of cost reduction, that is, making the energy cost of solar power nearly equivalent to that of fossil fuel, one must dramatically reduce the cost of raw materials and establish their stable supply. To this end, clarifying the allowable level of each impurity element, as described in Section 2-3, is indispensable, while sustaining the performance of solar cell power generation. However, an allowable level of impurities is inconsistent depending on ingot, wafer, cell, or module step, failing to elucidate the effects of each impurity on cells characteristics until now. In terms of solar grade high purity silicon production processes, it is important to clarify each nanoscale impurity behavior. Such research activities are expected to occur jointly at industry-government-university centers. In particular, universities with technology basis of materials science and government research institutions can play a big role. As an overseas example of industry-government-university institutions, Crystal Clear in the European Commission can be cited. With emphasis on silicon raw materials technologies, Crystal Clear is developing processing technologies of raw materials which are low cost and capable of generating sufficient electric power[24,25].

(1) Clarification of impurity behavior in grains and the boundary layers of silicon

In traditional manufacturing processes, wood chips and/or cokes are used to reduce silica in the first processing step, that is, silicon (Si) is produced from silica raw materials (SiO_2). Since wood chips and coke as a reducing agent contain impurities, such silicon is lower in purity than that of original silica raw material. Furthermore, carbon, a reducing agent, must be investigated as to how it remains in the grains and the boundary layers of silicon.

Research is being carried out in the removal of metallic impurities in the above mentioned metallurgical processing, using the principle that the metallic elements of smaller segregation factors at the silicon solid/liquid phase boundary (that is, iron, aluminum, titanium) are discharged into the liquid phase via the one-directional solidification method. These elements of smaller segregation factors are, as mentioned in Section 2-3, elements of particular interest for removal. For removing phosphorus, the electron beam vacuum melting method is used to drive off phosphorus preferentially through evaporation when silicon melt surface is locally heated. Boron and carbon are removed subject to oxidation by oxygen from water vapor, which is added to a plasma melting scheme.

In particular for polycrystalline silicon, the presence of grain boundaries (boundaries between crystals) creates crystal defects and/or complicates microstructures at grain boundaries due to impurities, making simple determination of impurity limit affecting the performance very difficult. Also, even for the single crystal case, it is necessary to find distribution and chemical states of impurities. Future research to achieve high purity will require understanding of composite defect structures and their formation mechanisms stemmed from grain boundaries, defects, and impurities, and above all how to inhibit them[25].

(2) Clarification of impurity behavior using nanoscale experimental analyses and computer simulations

For instance, according to the SPring-8 radiation light study, investigating iron distribution and its electronic state in the silicon crystal, the iron is found to situate in specific locations[17]. Hopefully, the nanoscale mechanisms may be elucidated through research regarding how impurities during production diffuse through silicon to form silicide (compounds formed by silicon and metals) deposits or what structural morphologies are formed with polycrystalline defects.

Conducting such research, computer aided materials design or simulation could become a revolutionary tool for developing high purification process technologies as referred to in the "Chemical Element Strategy to be adopted by Ministry of Education, Culture, Sports, Science and Technology"[26] which is described as an R&D subject in the Nanotechnology and Materials field in the "Third Science and Technology Basic Plan". With the first principle calculation and the molecular dynamics calculation, one can analyze impurity behavior in grains and the boundaries using the materials database that has accumulated through past materials research[27], making it possible to explore new simple and low cost processing technologies for high purification.

5-2 Need for innovative process technology development for high purity production

In order to lower power generation costs in accordance with the roadmap in Figure 1, significant cost reduction as well as a stable volume supply of silicon are required. As both electric power and module costs continue to decrease, so do raw materials costs. Under the premise that the silicon base solar cell maintains the mainstream, it will be difficult to achieve the power generation costs as targeted in the roadmap even though materials cost increase may possibly be mitigated or at least remain about the same.

In order to reach the goal, innovative production processing technologies aimed at dramatic cost reduction, as shown in Figure 5, must be also explored. To this end, it will be even more necessary to clarify the reduction mechanism of silica and the mechanisms for expression of characteristic features. For example, based on the concept that cheap solar grade silica is prepared first and then reduced to silicon while maintaining the same purity level, research was conducted focusing on electrochemical reduction. Since silica is by nature an insulator the electrochemical approach is difficult, but by feeding electrons externally, researchers found a way to electrochemically reduce silica into silicon[28-30].

5-3 Promoting production processing technologies with venture type organizations

Traditionally, silicon industries, including silicon manufacturing, require large scale facilities - only the affiliates of major semiconductor companies can participate due to large initial capital requirement. However, recent surveying of solar cell related companies show that more are distinctively based on venture type organizations. One of the reasons is because of great worldwide attention drawn to the solar cell industries, investment is made heavily even for venture type organizations. Another reason, however, is that throughout the solar cell industry including silicon, divisionalization is proceeding at each level. As a result, more than a few hundred companies have evolved, many of which are venture organizations and international cooperative companies. The situation resembles the era of warlords. This situation will last for a while, but eventually new multinational type companies will emerge from among the companies. For example, in China, there is a case in which a solar cell venture start-up from a university has succeeded big and is now listed on the overseas stock market.

Regrettably, however, there are very few newcomers in Japan — primarily traditional silicon industries. In commercializing frontier technologies, such as a nanotechnology, even if each company can make full use of operating resources such as their own technology and manpower and possibly benefits from the industry and academia consortium, each company may not find a good fit with its business strategy, and consequently, usually fails to create a new business. For introducing such technological accomplishments to the world, a venture type start-up should be created, while employing manpower, technologies, and aggressively promoting its market value[31].

Only new venture organizations should be involved in developing innovative silicon production process technologies if we consider requirements, such as new ideas not limited by the traditional raw materials processing technologies; a good match between seeds from raw materials suppliers and the needs of post-processing user sides; and minimal risks of small scale technologies. At the same time, such organizations require backing with technology seeds provided by universities or other public research centers. For instance, among a small number of such examples found in our country, a venture company, using R&D results from the Institute of Industrial Science, University of Tokyo, takes solar silicon waste from a semiconductor production plant, which is then melted in melting equipment under low pressure and hit with electron beam to vaporize impurities, making solar grade silicon[32].

It is difficult to see the market potential at the technology stage when commercializing new silicon raw materials technology that is created via nanoscale level research dealing with atoms or molecules and not an extension of any traditional technology. Accordingly, this is too great a risk for large companies. Especially, the downstream processing industries are too cautious, despite the market need, for investing the basic raw materials technology area due to lack of technical experience. Because of the complex nature of manufacturing processing steps up to product shipping, large companies tend to be less involved in the basic raw materials technologies, that is, those requiring substantial technical seeds. It is hard for a traditional company to single-handedly acquire or train the personnel necessary for researching such basic technologies. As a result, there is a great expectation for technical seeds provided by university and public research centers from Japan's solar cell industries including silicon materials technologies.

6 Conclusion

The expectation is that the market for solar cell power generation will continue to rapidly grow led by Europe and the U.S. as the world pays more attention to global conservation. The dissemination and expansion of solar power generation systems are heavily dependent on how much one can reduce power generation costs, and hence key technologies should be developed toward reducing the cost of solar power generation systems. In regard to solar cell materials, since solar power generation using silicon systems continue to be mainstream, the fear is that a supply shortage of raw materials could become a determining factor for future growth. In terms of measures against the shortage of high purity silicon, one long-term project is to deploy new structure cells consuming less silicon. However, since the traditional cell system will continue to be chosen in the near future while solar cell production increases, it is necessary to aggressively expand silicon production, reinforcing more refinement facilities as well as developing and/or introducing new process technologies. From a materials point of view, the highest priorities should be given to issues of securing a stable silicon supply and lowering silicon raw materials costs.

Up to now, major application of high purity silicon has been for semiconductors, but from now on, the semiconductor grade silicon will be a specialty product, making solar cell application the volume-wise major part. Under such circumstances, the role played by researchers involved in nanotechnology and materials science will be greater than ever in such areas as high efficiency power generation by solar cells, low cost manufacturing, and innovative refinement technology, among others. In particular, it should be taken into consideration to establish new venture type organizations and to utilize technical seeds provided by university and public research centers, through which promoting to commercialize technologies that are not the extension of traditional ones, that is, innovative process technology development for silicon production completely independent of the traditional raw materials manufacturing processes.

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