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Structure and Role of Silica in Plants

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Abstract

Specific unique structures of silica particles on the surface of leafs and stems of plants depending on the sorts of plants are studied and the roles of silica in these plants to keep their shape, have efficient energy harvesting and maintain their life in the severe environments are discussed in terms of optical, mechanical, thermal and biological view points. Interaction of micro-organisms such as bacteria, yeast and fungi etc. with silica is also discussed.

Recently organic-inorganic composite systems attracted great interest from practical view points for the application in industry. However, it should be mentioned that such organic-inorganic-systems- have been developed in plants in the long history of the development to fulfill specific purpose to survive in the severe environments of nature.

It is well known that much amount of silica is contained in most living creatures such as plants. Indeed the plants are composed of organic-inorganic systems which are also attracted much interest from industrial view points. However the roles of silica and processes of the formation of specific structures of silica bodies are not well understood so far. At least we can say that in plants organic-inorganic systems are formed in the mild condition at around room temperature and atmospheric pressure with highly efficient process in energy compared with artificial synthetic processes in industry.

There is no doubt that silica is inevitable for the life of plants, for growing, keeping shape, keeping long life surviving from the severe enviroment and also for prosperity of a descendant and so on.

That is, in the long history of evolution, biological systems such as plants found unique solution to the problems in harsh diversified of circumstances for survival.

Therefore, the formation of unique structures of orgainic-inorganic systems have been formed by living things, which can be called as biomineralization. Especially Si is one of the most widely used inorganic element in plants. That is, living thing uses what they can use from environmental. Si is the element of Clarke number 2.

we have reported various specific structure of silica in organisms such as plants, diatoms, rice, horsetail (***Equisetum hyemale***) and *Aphananthe aspera* and discuss the roles of the silica.

Recently we revealed the specific structure of silica bodies in diatoms in river and indicated that they play very important role for the photosynthesis process by increasing the interaction chlorophyll in diatoms with incoming light for photosynthesis.

We found unique structure of silica bodies on the leave of rice plants and explained their roles as to keep their shape, maintain well suited temperature under infrared light irradiation and also to protect from insects and some sorts of bacteria and fungi etc.

In horse tail, silica plays important role to make the stems mechanical strong shape and seal various liquids from a leak. We interpreted that in the early history of plants, silica played important roles until lignin and cellulose were highly developed.

At this moment we are interested in following points.

How much amount of silica are contained in various plants with what type of shapes?

What is the role of specific shape of silicas in plants? How the shape of silica bodies are formed? From where silica is introduced in plant bodies? Has the silica structure some specific meaning in the history of the earth? How the non-soluble silica turns into silicon derivatives absorbable from fine roots? Is it possible to apply the specific shape of silica bodies for some industrial applications? Is it possible to apply for some modern industrial processes, the processes to make silica solid into soluble form and to transfer to specific point and make specific shape of silica bodies?

We are also dreaming to obtain pure Si from silica by some biological technology.

Figure 1 indicates the photographs of fresh water diatoms. Figures 1(a), (b) and (c) are the whole shape of the living cells of diatom surrounded by silica glass frustule observed by an optical microscope, frustule with cup like structure observed by a field emission scanning electron microscope (FE-SEM) and the surface of the outer layer of the frustule also observed by FE-SEM, respectively[1].

In diatom cells chlorophyll is attached to the inner surface of frustule of 15~20 μ m in diameter

As shown in Fig.1(b) on the surface of the outer surface of diatoms, regular array of holes with periodicity of about 200nm are formed. This indicates that frustule has honeycomb structure.

We analyzed this periodic structure in terms of interaction with light by the theory of photonic crystal. That is, we theoretically analyzed the optical property of diatom under the assumption of the honeycomb structure of the diatom with regular array of triangular-lattice holes.

Typical photonic crystal band gap structure was obtained in this case of the diatom. At the band edge large anomaly was discovered, which results in the slow down of the light velocity. From this

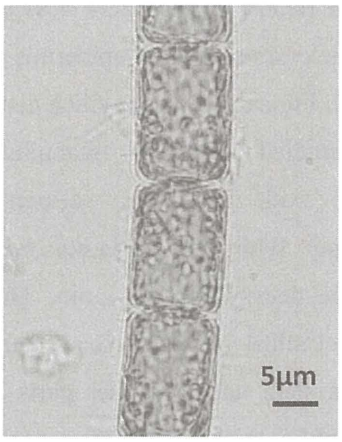

Fig.1(a) Photographs of the whole shape of the living cells of diatom.

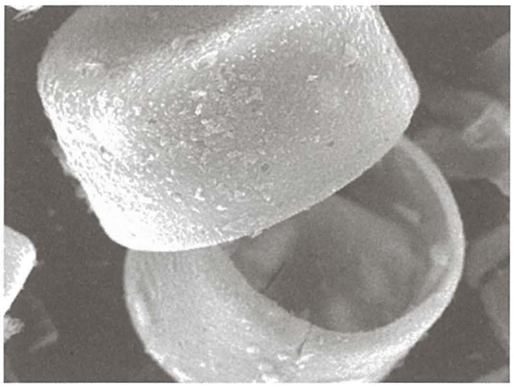

Fig.1(b) FE-SEM image of frustule with cup like structure.

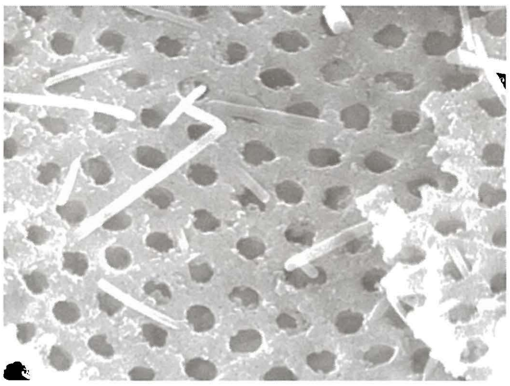

Fig.1(c) FE-SEM image ofthe surface of the outer layer of the frustule.

result we interpreted that the diatom with such a specific structure play roles to make the velocity of some wavelength of light slow down, which results in the higher efficiency of photosynthesis by chlorophyll inside the diatom.

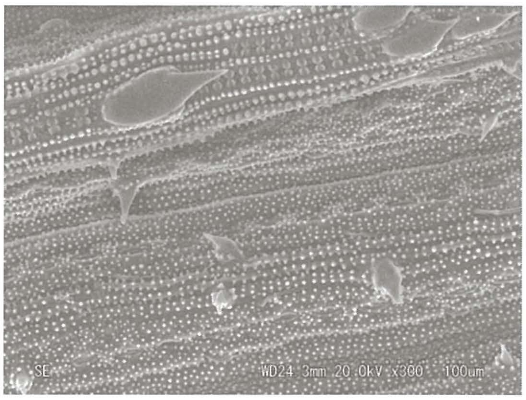

Fig.2 SEM image of the epidermis of the rice plant.

Various unique structure of silica bodies were found on the leaf of rice. Rice opals have been found in soil as the residue of rice plants containing silica in ancient age. It is well known that the rice opal as one of a plant opal formed by silica bodies excavated from soil has been very important in the paleontology and archaeological studies to estimate history.

Figure 2 shown SEM image of the epidermis of the rice plant. There are several different shapes of silica particles. That is, the first type is small silica particles of grain size around 1 μm in diameter and dispersed with separation of around 5.6 μm, the second type is a ladder-like structure and the third is the trichomes of silica[2].

We have studied physical meaning of these specific shape of silica bodies.

The dispersion of small silica particles are not completely regular. However by the assumption as a two-dimensional triangular lattice type of distribution, we theoretically calculated photonic band structure and found anomaly at around 9.8 μm. It should be mentioned that this wavelength in infrared region corresponds to the peak of a black body curve at the temperature of 20C. This means this dispersed silica particles should play important role to keep the temperature fit to the growth of rice at good condition .

We also theoretically calculated mechanical effect of the ladder type structure and came to the idea that this plays role to keep the leaf flat and inhibit the flat leaf from undergoing twisting torsion, so that the leaf absorb sun light more effectively.

Horsetail (Equisetum hyemale) contains much amount of silica and is also very famous as an ancient plant.Fig.3(a) is typical Horsetail found in a garden. We can also find longer Horsetail as shown in Fig.3(b).. In ancient time, much longer Horsetail family of the tree existed.

We have studied distribution of silica in the stem of horsetail[3]. The stem of horsetail has the structure of hollow pipe. Figure 4(a) is the SEM image of the cross-section of epidermis of the stem of horsetail. Figure 4(b) is the silica distribution in Fig.4(a) studied by the scanning electron microscope with an energy dispersive X-ray spectroscope. With this apparatus we can also evaluate the distribution of lignin. These results indicate that silica is mainly located at the outer area of the stem and the other parts are mostly composed of lignin and cellulose.

We also made mechanical study and calculation and come to idea that silica also play roles to contribute to mechanical strength in the early history of plant, when lignin may be not well developed.

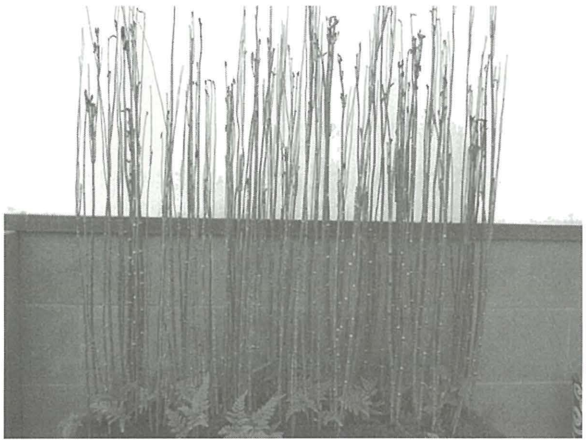

Fig.3(a) Photograph of normal horsetail.

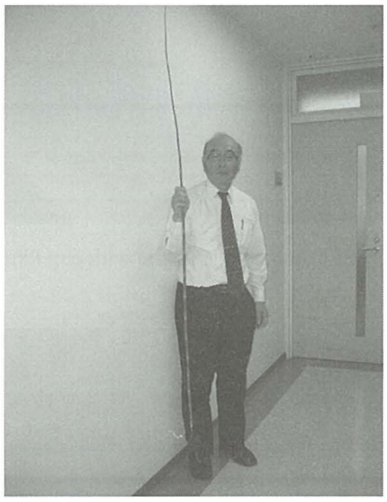

Fig.3(b) Photograph of long horsetail.

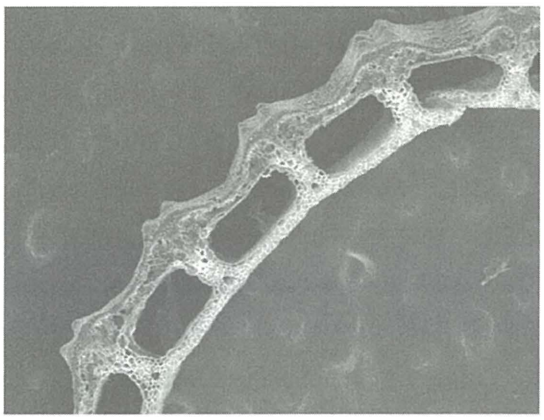

Fig.4(a) SEMimage of the cross-section of epidermis of the stem of horsetail.

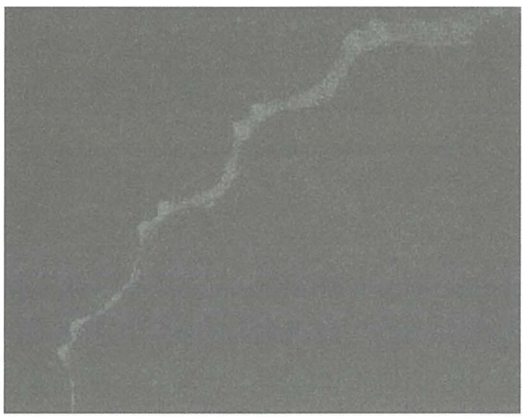

Fig.4(b) Silica distribution in Fig.3(a).

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We also studied a leaf of muku-tree (Aphananthe aspera)

The leaf of the 'mukutree (a tree of the elm family muku:Aphananthe aspera) has been used for smoothing the surface of wood cups for lacquer ware, which means much amount of silica is also contained in the muku-tree. Indeed, we found unique trichomes structure on the surface of leaves of the muku-tree as shown in Fig.5. It should be mentioned many silica particle are contained in these trichomes. We are now under study what roles this nearly regular array of trichomes are playing. Many effects such as photon harvesting or keeping temperature by the interaction with infrared light, except for the anti-biological effects for bacteria and so on, may be probable.

As already mentioned we are also much interested how the plant absorb silica through roots. At least some water soluble silica derivatives must exist or formed in water for example in rice fields.

It is obvious that these specific shape of silica are obtained from the soil through fine roots of the plants. Especially it should be noted that usually in Japan rice was grown in the rice field filled with water. That is, water is very important for the growth of rice. It means the silica was turned to soluble form in water. That is, some thing like bacteria, fungi etc. must have made the silica existing on the earth to soluble derivatives.

Indeed there exist several types of fungi which interact with silica. For example, Figure 6 indicates the trace on the silica plate invaded and the hollow

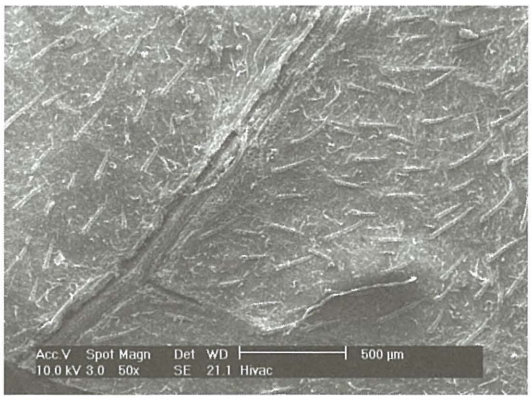

Fig.5(a) SEM image of the surface of a leaf of the muku-tree.

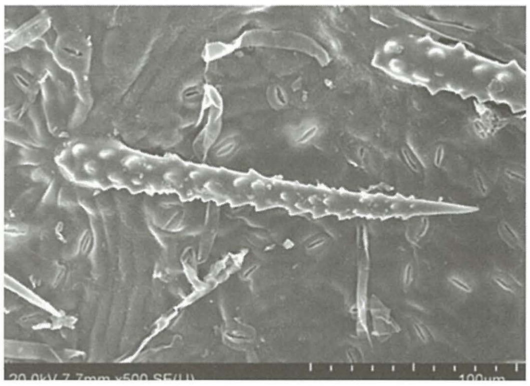

Fig.5(b) SEM image of the trichome on the surface of leaf of the muku-tree.

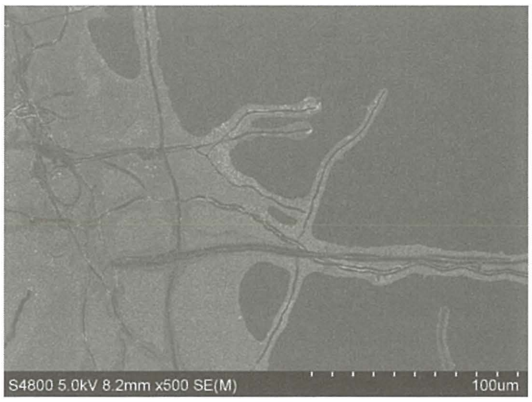

Fig.6(a) SEM image of the surface of the silica plate invaded by fungi, Fusariumoxysporum.

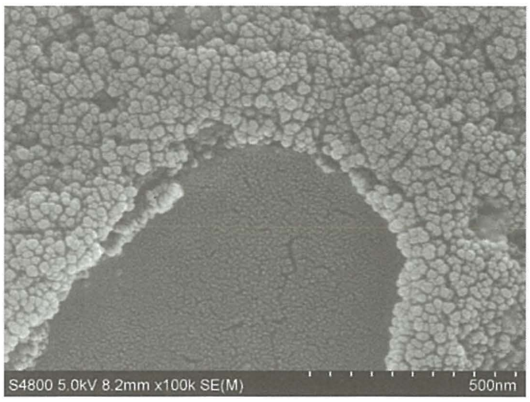

Fig.6(b) Magnified SEM image of the caved hollow on the surface of a silica plate.

which was formed on the surface of a silica plate by the effect of fungi, Fusarium oxysporum.

As evident in Fig.6(b) surrounding the caved hollow, many nano-scale silica particles are found. These particles are confirmed to be silica. We are studying why such nano-paraticle of this shape was obtained. We are also interested whether the hollow forming effect can be applied in industry for the precision cutting process of silicon related materials.

Similar silica particle have also found in other systems due to the effect of Fungi. In water the silica may be turned into soluble forms, such as some ionic species. During this process silica may be absorbed through fine roots. Something (material or energy) may be delivered from the plant through roots to help activity of fungi.

We are looking for new organisms such as bacteria, fungi and so on which eats or treats silica.

At last it is our dream to find some bacteria or fungi to react with silica effectively and make pure Si from silica SiO_2. Some aerobic organisms such as aerobic bacteria which contacted with silica under oxygen free condition, may take oxygen from silica, resulting in the Si formation. Furthermore we may be able to get pure Si economically by biological process to use these organisms instead of expensive industrial process.

References

1) S. Yamanaka, R. Yano, H. Usami, N. Hayashida, M. Ohguchi, H. Takeda and K. Yoshino; J. Appl. Phys. **103**, 074701 (2008)

2) S. Yamanaka, H. Takeda, S. Komatsubara, F. Ito, H. Usami, E. Togawa and K. Yoshino; Appl. Phys. Lett. **95**, 123703 (2009).

3) S.Yamanaka, K.Sato, F.Ito, S.Komatsubara, H.Ohata and K.Yoshino; J.Appl.Phys. 111 to be published