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Technical note

Formation mechanism of hollow silicon ingot induced by fountain effect

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ABSTRACT

A hollow silicon ingot was obtained by a solid–liquid separation method inducted by the fountain effect and the formation mechanism of the ingot was also discussed. A layer of solidified shell was formed on the melt surface and the gas dissolved in the melt was separated out. Because of this, the thickness of the shell was gradually increased and expanded due to the sudden change of the chamber pressure leading to the silicon melt being squeezed out from the preset hole of the shell. During this process, the melt left behind contains a high concentration of impurities and can be separated or detached completely from the decontaminated solid. This novel approach has of great potential to inhibit the back diffusion of impurities and to produce a silicon ingot at a high yield rate.

1. Introduction

In modern years, the demand for solar-grade silicon has been increased dramatically with the rapid development of the photovoltaic industry [1–4]. Cast multicrystalline silicon is the main raw material for the production of solar cells, which occupies more than 80% of the market share [5,6]. However, the yield rate of cast multicrystalline silicon is less than 70% due to the back diffusion behavior of metal impurities in silicon ingot, leading to near 10% of each ingot cannot be used for solar cells. The current global annual production of cast multicrystalline silicon is more than 100,000 t, so every year more than 10,000 t silicon is lost.

During the casting process, contaminants are redistributed in the silicon ingot, but not eliminated. When silicon solidifies, the contaminated accumulation region is discarded and the purity of the rest is enough to meet the high performance standard necessary for solar cells. The allotment of contaminations shows an increasing trend from the bottom to the top due to the segregation from the liquid-to-solid phase in the central regions of the ingot. This brings into being high concentrations of what near the top of the ingot, which subsequently diffuse back into the ingot during the cooling process [7,8], leading to a significant reduction of the ingot yield. However, only few reports on the inhibition of back diffusion are available to date.

If the concentration distribution by Scheil's equation is regarded as the initial condition, the diffusion flux at the bottom is considered to be 0 and the concentration at the top is considered to be constant, thus, the concentration of the impurities as a function of the height and time can be calculated, as shown in Fig. 1. According to Scheil's equation, the iron concentration under the ingot height of 79% is less than 0.1 ppm. After diffusion for 1800 s, the area where the iron concentration is less than 0.1 ppm only accounts for about 51% of the whole ingot. There is a strong back diffusion behavior occurring in the top of the ingot due to a large concentration gradient, leading to the decrease of the yield rate by 28%. If the melt with high impurity concentration is separated from the solid which has been purified, the yield rate of the ingot cannot be affected by the effect of impurity accumulation region.

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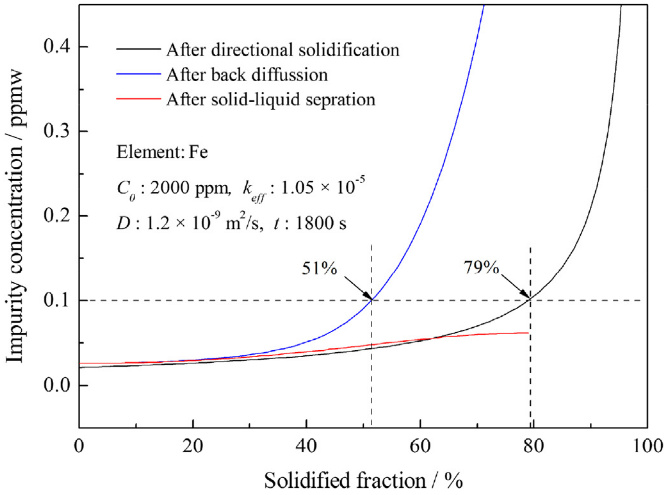

Fig. 1. Simulation of iron distribution in silicon ingot.

At the end of the casting process, a lot of contaminants concentrate in the liquid phase which has not yet solidified. If this liquid can be separated from purified silicon crystal, then the driving force for the back diffusion of impurities can be greatly weakened. This mechanism is regarded as a promising way to inhibit back diffusion and enhance the yield of the ingot. In this paper, a solid–liquid separation method is executed by the induction of the fountain effect to form a giant gas hole in a silicon ingot, which can condense the contact area of the contaminations accumulation region and the purified region so that the back diffusion behavior is inhibited.

2. Principle of solid–liquid separation by fountain effect

A solid–liquid separation method initiated by the fountain effect is proposed to inhibit the back diffusion behavior of the impurities. The schematic illustration of this method is shown in Fig. 2. First of all, silicon is melt entirely in a crucible under low vacuum condition. Consequently the melting power is reduced so that silicon melt start to solidify slowly from the bottom to top. If the silicon solidifies completely in such a way, a normal directional solidified silicon ingot can be obtained and a small part of silicon melt could be squeezed out of the top due to volume expansion during the cooling process.

If when the crystal goes up to a preset height, the vacuum system is established to diminish the chamber pressure quickly, so that silicon evaporates rapidly into the gas phase. It takes away huge heat, so that a deposit of solidified shell forms on the melt surface due to a sudden temperature drop of the melt. At this flash, a quartz pushrod which is set above the melt is used to prod a hole in the center of the solidified shell. Soon after, the power is shut off so that the left behind melt solidifies hurriedly. During this process, the gas suspended in the melt will be separated out, accumulated and expanded. The gas cannot be vented due to high viscosity of silicon melt at the temperature close to the melting point. Hence, the melt is squeezed out from the center hole of the shell and separated from the purified region. After the melt solidifies completely, a big gas hole forms inside the ingot, which reduces the contact area of the contamination accumulation region and the purified region to inhibit the back diffusion behavior of the impurities. The solid–liquid separation process looks like a fountain, why it is called the fountain effect.

3. Experimental

Two casting experiments were carried out in a vacuum induction melting furnace. 900 g MG-Si feedstock was used in this experiment. Prior to processing by melting and solid–liquid separation, it was washed adequately with supersonic wave cleaner in alcohol to remove potential solid residues and superfluous contaminations from the surface. Consequently, the silicon was melted in the quartz crucible with a diameter of 10 cm, which was carried out in an argon gas atmosphere. After melted completely, the molten silicon was set to temperature of 1773 K and a set chamber pressure of 4 × 10^4 Pa for 1 h.

For one of the experiments, the crucible was pulled downward out of the induction coil so that the silicon solidified slowly from the bottom to the top. When the silicon solidified completely, the power was shut off.

For another experiment, the crucible was pulled downward out of the induction coil so that the silicon solidified slowly from the bottom to the preset height. After that, the vacuum system was started to rapidly reduce the chamber pressure to 2 × 10^3 Pa. When a solidified shell formed, a quartz pushrod was used to poke a hole in the center of the shell, and then the power was shut off.

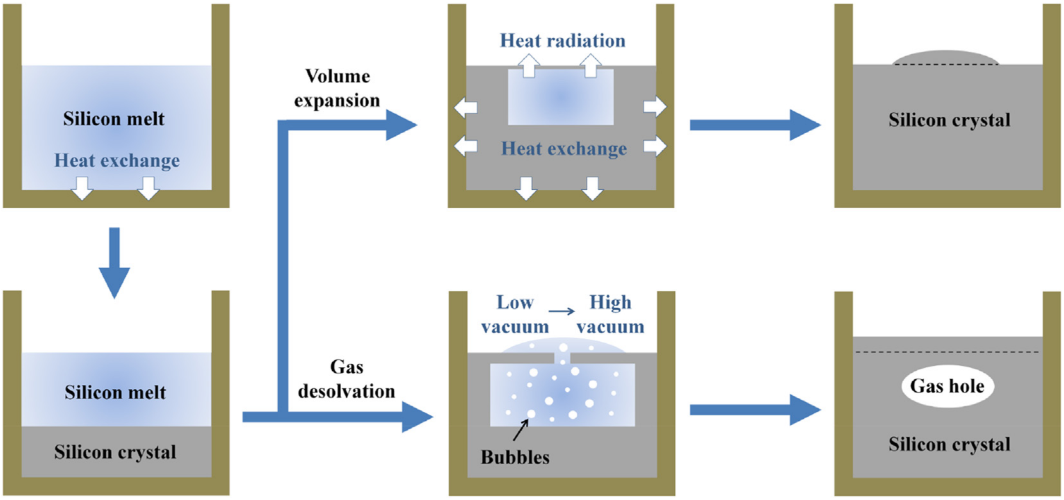

Fig. 2. Schematic illustration of solid–liquid separation method induced by fountain effect.