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Electrical resistivity distribution of silicon ingot grown by cold crucible continuous melting and directional solidification

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ABSTRACT

A multicrystalline silicon ingot was grown by cold crucible continuous melting and directional solidification. The electrical resistivity, shallow level impurities' concentrations and microstructure of the ingot were measured, and their relationships were studied and discussed. The results show that in the vertical direction the electrical resistivity gets its maximum value at the height of 90 mm and then decreases toward both sides. In the horizontal direction, it is distributed uniformly in the inner area and increases slightly in the peripheral area. The electrical resistivity of the silicon ingot is affected by its shallow level impurities' concentrations and its microstructure. Among these impurities the effect of Al is less than those of B and P, since Al tends to form complex precipitates with other elements.

1. Introduction

Solar energy will shortly be in great demand since it is infinite and cleaner than traditional energy resources, such as oil, coal and natural gas [1]. To date, since the growing photovoltaic industry is mainly based on silicon solar cells, reducing the cost of silicon wafers is of great significance [2]. Due to the advantages of low production cost and relatively high conversion efficiency, multicrystalline silicon wafers have become the main materials used in photovoltaics (PV). These wafers are commonly cast by directional solidification and then sliced by wiresaw slicing [3,4]. Because quartz or ceramic crucibles are used during directional solidification, crucible contamination and consumption are inevitable [5,6]. Meanwhile, the cycle of ingot growing is usually long. So, further improvement of silicon ingot casting technology is required for the long-term development.

Cold crucible continuous casting is a novel technology that enables fast growing of silicon ingot with low or no crucible contamination and consumption [7]. Researchers from France, Japan, USA and Germany have carried out studies on this topic and some achievements have been achieved [8]. However, due to the strong cooling of the cold crucible wall, the crystal growth direction often deviates from the pulling direction and the defect density is relatively high, and both of them need to be further studied and improved [9,10]. By controlling induction heating and strengthening bottom cooling, multicrystalline silicon ingot 60 mm × 60 mm in cross section has been directionally solidified by cold crucible continuous casting in our research group, as reported in Ref. [11]. This paper reports the latest research work that is done on the basis of a previous study, and it focuses on the electrical properties of the ingot that is directionally solidified by cold crucible continuous casting. Many researchers have studied the electrical

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properties of silicon ingot cast by conventional directional solidification, and the results showed that compensation between the donor and acceptor impurities has a significant effect on the electrical properties of the ingot when the raw material is co-doped or its purity is low [12,13]. Then, in this paper the B, P and Al concentrations of the ingot directionally solidified by cold crucible continuous casting were measured, and their effect on the electrical properties of the ingot was investigated. Meanwhile, the effect of microstructure was also studied and discussed.

2. Experimental methods

A schematic diagram of the experiment is shown in Fig. 1. As shown in Fig. 1(a), the dynamic part in cold crucible continuous melting and directional solidification process is the molten zone. This is continuously fed with silicon granules, heated by induction heating and then continuously cast into one ingot. Since silicon is a semiconductor, a graphite base was used to startup the heating and melt silicon granules at the beginning. More details of the startup heating, continuous melting and directional solidification processes were reported in Ref. [14]. And as reported in Ref. [15], for obtaining the directionally solidified silicon ingot by cold crucible continuous casting, the experimental parameters used in this study are as follows: the pulling velocity is 1.5 mm/min, the input power is 50 kW with frequency of 50 kHz and the initial heat preservation time is 8 min. The raw material is metallurgical grade silicon, and its chemical composition is shown in Table 1. The cross section of the cast ingot is 60 mm × 60 mm, and its length is approximately 120 mm. The ingot was cut in the middle along the pulling axis and parallel to one side into two halves, as shown in Fig. 1(b). One half was used to measure B, P and Al concentrations by ICP-AES, and six samples were taken from this half to measure the impurities' concentrations, as shown in Fig. 1(c). The measurement errors of B, P and Al concentrations are less than ten percent of the measured values. The other half was used to examine the electrical properties of the ingot and its microstructure. The electrical resistivity and conduction type were measured by SEMILAB RT-100 and SEMILAB PN-100 respectively. The positions measured are shown in Fig. 1(d); measurements were taken every 5 mm in the vertical direction and 7 mm in the horizontal direction, along the dotted lines. The microstructure was characterized by an optical microscope (OM) and a scanning electron microscope (SEM) with an Energy Dispersive Spectrometer (EDS).

3. Results and discussion

3.1. Electrical resistivity distribution along the vertical direction

Silicon ingot was directionally solidified by cold crucible continuous casting. The structural features of the ingot are similar to that reported in Refs. [11, 15]. Except in the peripheral zone, most of the grains are preferentially aligned parallel to the pulling direction and columnar grains distribute almost in the whole section from the bottom to the top. The electrical resistivity distribution along the vertical direction is shown in Fig. 2. It shows that the electrical resistivity gets its maximum value at the height of 90 mm and then decreases toward both sides. Furthermore, it can be seen from the figure that the electrical resistivity distribution profile at the heights from 70 mm to 100 mm is steeper than that of any other

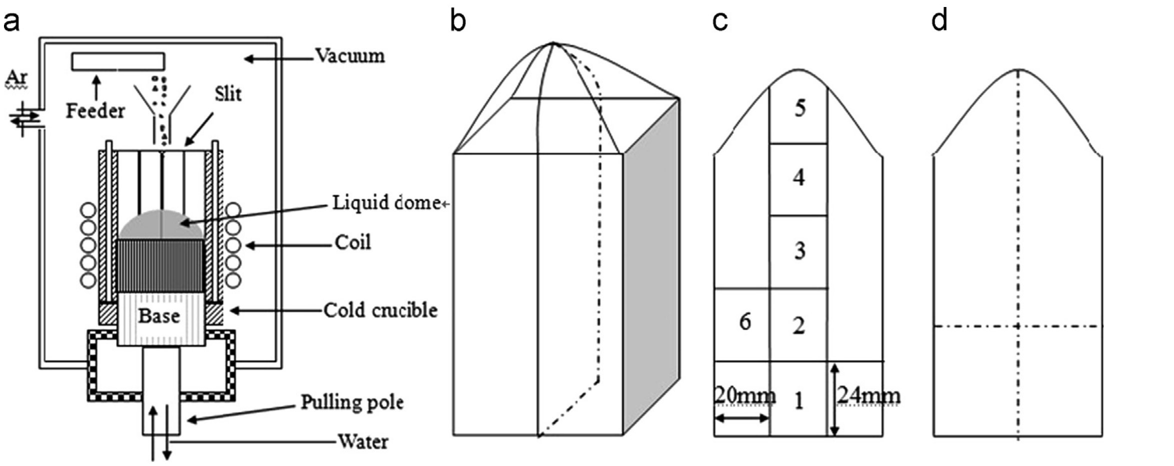

Fig. 1. Schematic diagram of experiment: (a) ingot casting, (b) half cutting, (c) sampling for impurities' concentrations measurements, and (d) positions for electrical resistivity and conduction type measurements.

Table 1
Chemical compositions of the silicon used in this study.

Elements	Al	Ca	Cu	Fe	Ti	Ni	C	O	B	P
Content (wt%)	0.22	0.21	0.006	0.4	0.025	0.0068	0.024	0.014	0.003	0.0038