Renewable and Sustainable Energy Reviews 32 (2014) 936–943

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Recovery of solar grade silicon from kerf loss slurry waste

Nadjib Drouiche [a,*], Patricia Cuellar [b], Fouad Kerkar [a], Sidali Medjahed [a], Nabila Boutouchent-Guerfi [a], Malek Ould Hamou [c]

[a] Centre de Recherche en technologie des Semi-conducteurs pour l'Energétique (CRTSE). 2, Bd Frantz Fanon BP140, Alger–7 merveilles 16027, Algeria
[b] Process Engineer Water Treatment, ManEngenius, The Netherlands
[c] Laboratoire Pédagogique du Génie Minier, Département de Génie Minier de l'Ecole Nationale Polytechnique (ENP), Alger, Algeria

ARTICLE INFO

Article history:
Received 7 November 2013
Received in revised form
9 January 2014
Accepted 27 January 2014
Available online 14 February 2014

Keywords:
Kerf loss
Silicon carbide
Silicon recovery
Photovoltaic
Electric field
Centrifugation

ABSTRACT

During the last two decades and, particularly, in recent years, the photovoltaic sector has increased interest in the recovery of solar grade silicon (SOG). In order to further develop related technologies and to find suitable commercial applications for its recovery, it is essential to understand the current scientific know-how and advances. This review paper copes with recently published scientific articles in which the recovery of solar grade silicon has been studied. In addition, the present work provides an updated picture of the current understanding of the theory behind the employed technologies. The techniques discussed were divided into six categories, which are: (i) alloying process, (ii) hydrobromination, (iii) supercritical water, (iv) electrophoresis and gravitational settling, (v) directional solidification, and (vi) centrifugation.

Contents

1. Introduction

In the past few years, the availability of polysilicon feedstock has been a critical issue for the rapidly growing PV industry. The tight supply situation has caused very high polysilicon spot market prices (up to 260 €/kg in 2008) and has limited production expansion by the industry.

* Correspondence to: Centre de Recherche en technologie des Semi-conducteurs pour l'Energétique (CRTSE). 2, Bd Frantz Fanon BP140, Alger – 7 merveilles, 16027, Algeria. Tel.: +213 21 279880x192; fax: +213 21 433511.
E-mail addresses: nadjibdrouiche@yahoo.fr, droui2@unesco-ihe.org (N. Drouiche).

http://dx.doi.org/10.1016/j.rser.2014.01.059
1364-0321

On the other hand, polysilicon has triggered a rapid innovation in wafer production and cell manufacturing lowering the silicon consumption per W of module power produced. Silicon usage is currently 7 g/W, whereas it was typically 10 g/W for the year 2007. As an important fact, the reduction of silicon is of high priority, nevertheless, since the feedstock price has now been reduced, the pressure to reduce silicon usage has lately diminished.

Crystalline silicon modules are manufactured in six steps: (i) silicon production, (ii) silicon purification, (iii) silicon crystal growth, (iv) ingot slicing, (v) cell fabrication and, (vi) device processing for encapsulation. Given that, the cost distribution is dominated by the silicon wafer manufacturing, the solar silicon grade recovery is seen as an important parameter in low-cost manufacturing (Fig. 1).

Solar grade silicon (polysilicon) is the basic ingredient of crystalline silicon modules. It is melted and solidified using a variety of techniques to produce ingots with different degrees of crystal perfection. The most relevant crystallization technology is directional solidification. It is based on either single-crystal silicon grown by the Czochralski (Cz) method (2010: 33% of the market) or polycrystalline silicon by casting (2010: 53% of the market) [1].

The ingots formed by both methods are sliced into thin wafers by wire sawing. Wafers are processed into solar cells and interconnected in weatherproof packages designed to last for at least 25 years. A layer of silicon of about 250 μm thick is lost per wafer, representing more than 30 wt% of the silicon value.

The kerf loss goes into slurry waste during the processing and it is compounded by silicon, silicon carbide, metal fragments and mineral-oil-based or glycol-based slurry vehicle. It can be considered as a new source of production of low-cost solar-grade polysilicon feedstock material with the potential to recover enough polysilicon to generate over 300 MW/year of crystalline silicon solar cells, i.e., more than two times the size of the current silicon solar-cell production.

Recently, silicon recovery from the kerf loss slurry waste has attracted incessant attention on the separation of the components due to the high purity silicon material. Several purification methods have been developed for the removal of SiC such as: alloying process [2], hydrobromination [3,4], supercritical water [5], electrophoresis and gravitational settling [6,7], Phase-transfer separation method [8], and centrifugation [9–11].

This work aimed to review studies conducted mainly during 2008–2013, covering a wide and versatile range of feasible techniques applied in the recycling of silicon cutting kerf loss.

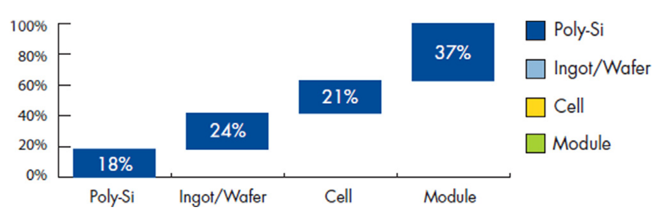

Fig. 1. Relative cost distribution of the production of crystalline silicon PV module.

2. Background

2.1. Semiconductor grade silicon production

The silicon PV industry has been relying on waste materials from the semiconductor Si industry regarding the feedstock material used in crystal growth. The waste material needed by the PV industry amounts to about 10% of the polysilicon material used by the semiconductor Si industry.

Semiconductor-grade polysilicon is mostly produced by the trichlorosilane ($SiHCl_3$) distillation and reduction method (Fig. 2) [12,13]. The trichlorosilane is manufactured by fluidizing a bed of fine pulverized metallurgical-grade silicon (MG-Si) with hydrogen chloride in the presence of a copper-containing catalyst. The MG-Si, is produced by the reduction of natural quartzite (silica) with coke (carbon) in an electric arc furnace. It can be noticed that the semiconductor-grade polysilicon material produced by this method far exceeds the purity requirement of the PV industry [14,15].

The main reactions that take place during the semiconductor Grade Silicon (SGS) production steps are:

1. Production of metallurgical grade silicon (MGS) by heating silica with carbon.

   $C\ (s) + SiO_2\ (s) \rightarrow Si\ (l) + SiO\ (g) + CO\ (g)$

2. Purification of MG silicon through a chemical reaction to produce a silicon-bearing gas of trichlorosilane ($SiHCl_3$).

   $Si\ (s) + 3HCl\ (g) \rightarrow SiHCl_3\ (g) + H_2\ (g) + \text{heat}$

3. Reaction of $SiHCl_3$ and hydrogen in a process called Siemens to obtain pure semiconductor-grade silicon (SGS).

   $SiHCl3\ (g) + 2H_2\ (g) \rightarrow 2Si\ (s) + 6HCl\ (g)$

2.2. Principles of wafer slicing

Wafer slicing, also called "wafering", is a key part of the solar photovoltaic (PV) cell manufacturing process. The wafering process begins with solid ingots made of single-crystal or multi-crystalline

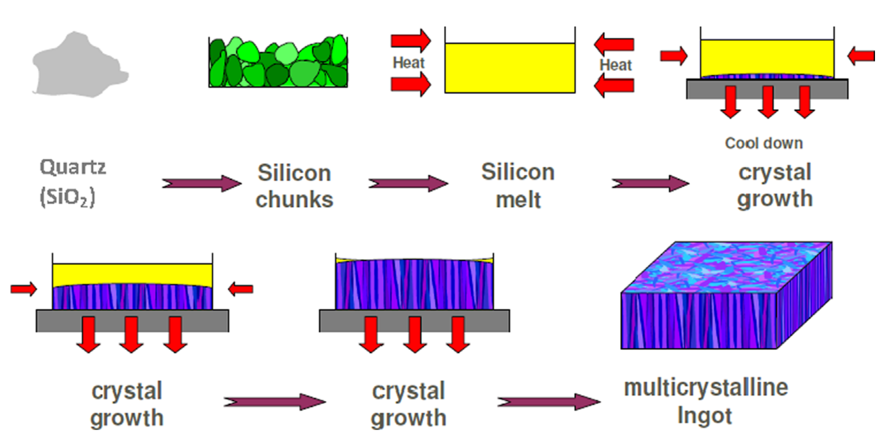

Fig. 2. Multicrystalline ingot manufacturing steps.