Polysilicon production technologies in a volatile market

Johannes Bernreuter, Bernreuter Research, Würzburg, Germany

ABSTRACT

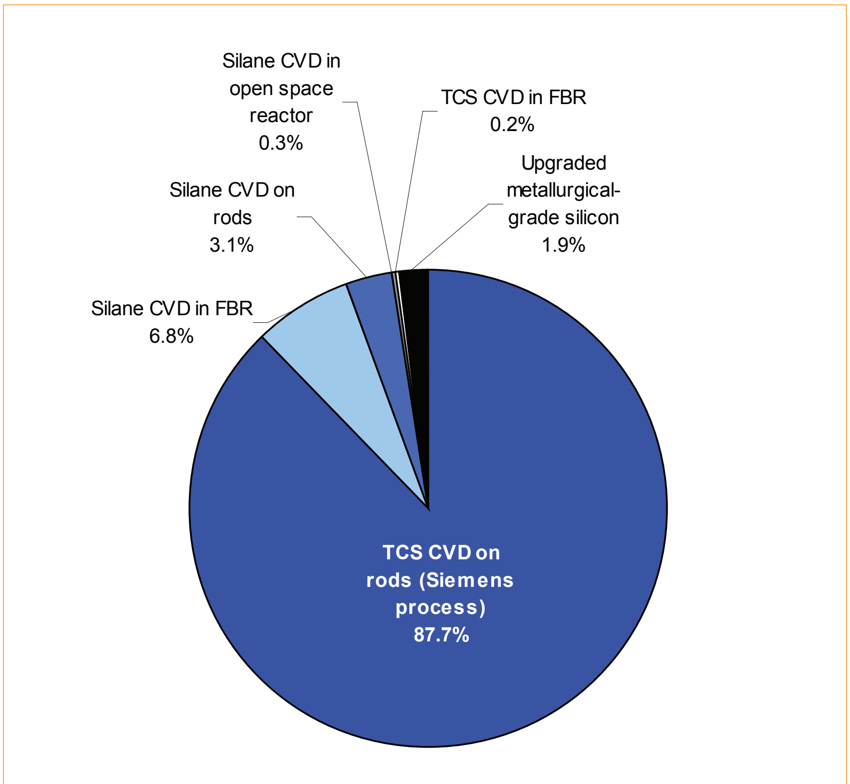
A record-low spot price in the wake of oversupply and the aggressive cost-reduction roadmap of the PV industry are putting polysilicon producers under pressure to bring down their manufacturing costs. With the dominant Siemens process approaching a limit for further cost cuts, technologies based on the deposition from monosilane (SiH_4) have now become the focus of attention.

Challenge of a cyclical business

After the polysilicon spot price began its five-year-long rally from a low of US$24/kg in 2003, the reaction took a while; but then, new production facilities were springing up like mushrooms in China. A lot of them were small 'chanterelles': 19 of the 43 Chinese polysilicon manufacturers in 2011 had an annual production capacity not larger than 1500 metric tons (MT), and eight of these were even 500MT or under. Such mini plants did not use a closed loop for recycling the vent gas silicon tetrachloride and consumed more than 300kWh of energy for 1kg of polysilicon, resulting in manufacturing costs of up to $70/kg.

This was a business model built on a perpetual high spot price, not on reality. Clearly, those small entrepreneurs were unaware of one fundamental characteristic of the polysilicon business: its cyclic nature. Since the engineering, construction and ramping-up of a new polysilicon plant can easily take three years, supply will always lag behind demand, leading to a regular cycle of oversupply and shortage phases with strong price fluctuations.

Now that the spot price has crashed from its high of $500/kg in 2008 to a record low of $15/kg, even the largest Chinese polysilicon manufacturers feel the brutal pressure of oversupply. They have successfully applied to the Chinese Ministry of Commerce for an anti-dumping and countervailing-duty investigation of polysilicon imports from the USA, South Korea and Europe – an obvious reaction to similar investigations in the USA and the European Union on China-made wafers and solar cells. Such tit for tat, however, does not solve the real problem. The polysilicon industry in China needs to work on reducing manufacturing costs and improving the product quality.



Source: Bernreuter Research

Figure 1. Market shares of technologies in the polysilicon production volume of 2011.

"A widely accepted, yet aggressive, target for the manufacturing costs of crystalline silicon solar modules is approximately 0.5US$/W by 2016."

Pressure from the PV industry

Although prices will recover on their way to the next shortage, which Bernreuter Research expects to happen in 2016, manufacturers cannot rest on this perspective. Since 1998 the share of the PV industry in polysilicon demand has risen from practically zero to almost 90%. Thus, the radical cost-reduction roadmap of its most important customer will have far-reaching implications for the polysilicon industry.

A widely accepted, yet aggressive, target for the manufacturing costs of crystalline silicon solar modules is approximately 0.5US$/W by 2016. Based on long-term contract prices, the share of the polysilicon feedstock in total module manufacturing costs has been varying in a relatively narrow band of 15 to 20% over the last few years. If this share is not to exceed 20%, and the average specific silicon consumption decreases to 5g/W by 2016, a polysilicon price of $20/kg will be required. Obviously, this is not a sustainable level for manufacturers. Their customers will be forced to further reduce the specific silicon consumption and to accept that polysilicon will take a higher share in the module cost structure. With 4.5g/W and a share of 25%, a price of nearly $28/kg would still be tolerable.

The high cost pressure, however, could promote a new trend in the PV industry towards fully integrated production from polysilicon to module in order to shave the profit margin of another step in the value chain – in particular when a new shortage drives up the polysilicon price considerably. The pressure is high because module manufacturers will hardly be able to fully pass on such a price increase to the end customer: there will be no generous solar incentives available that could cushion a module price hike of 30% as there were during the bottleneck between 2004 and 2008.

Cost limit for the Siemens process

For the reasons mentioned above, it is therefore in the polysilicon producers' interest to bring down their manufacturing costs as well. The dominating technology – the Siemens process – has been very successful in achieving a significant reduction of costs over the last decade, resulting in a market share of 88% in 2011 (Fig. 1). This development has mainly been driven by an enormous increase in the productivity of reactors for the chemical vapour deposition (CVD) of silicon from trichlorosilane (TCS) and by hydrochlorination as a more efficient technology to recycle silicon tetrachloride back to TCS. In October the equipment supplier GT Advanced Technologies, Inc. (GTAT) announced a new hydrochlorination fluidized bed reactor (FBR) for plants with an annual polysilicon production capacity of more than 10,000MT; according to GTAT, it allows cash costs to be reduced to less than $14/kg. Assuming a depreciation rate of $6/kg to $8/kg, this would result in manufacturing costs of $20/kg to $22/kg.

Most experts, however, agree that the air is getting thin for the Siemens process to improve on $20/kg. One should not let oneself be blinded by the figure of $18/kg that GCL-Poly Energy Holdings Ltd. claims for its subsidiary Jiangsu Zhongneng Polysilicon Technology Development Co., Ltd., China's largest polysilicon producer. Its actual manufacturing costs are substantially higher.

> "Bernreuter Research has identified technologies based on the CVD from monosilane as a viable alternative to the Siemens process."

In the current polysilicon market report "The 2012 who's who of solar silicon production" [1], Bernreuter Research has identified technologies based on the CVD from monosilane (SiH_4, also referred to in short as silane) as a viable alternative to the Siemens process. Just one week after this result was presented during the 27th European Photovoltaic Solar Energy Conference (EU PVSEC) in late September 2012 [2], GCL-Poly announced it had accomplished the trial run of its first-phase monosilane production system and was working on FBR technology to manufacture polysilicon from monosilane.

Deposition from silane on rods

CVD from monosilane is anything but a new technology in the polysilicon industry. In the second half of the 1970s, Union Carbide Corp. (UCC) developed a catalytic disproportionation process that converts TCS via dichlorosilane and monochlorosilane into monosilane; in 1984 the company opened a polysilicon plant in Moses Lake, Washington, USA, which was later run by Advanced Silicon Materials Inc. (ASiMI) and is today owned by REC Silicon Inc. The design of the CVD reactors was developed by Komatsu Electronic Metals Co., Ltd.; it is optimized to achieve extremely smooth and uniform polysilicon rods that can be converted into monocrystalline ingots for the semiconductor industry through the float-zone method.

Because of this optimization process, the deposition rate in the Komatsu reactor is very low, with a rod diameter growth of only 0.5mm/hour, compared to a rate of 1–2mm/hour in a TCS-fed Siemens reactor. Moreover, the Komatsu reactor cools each single silicon rod individually in a separate chamber, which consumes a lot of energy. This design has to do with a specific property of SiH_4: at temperatures above 500°C, it readily decomposes into silicon dust and H_2 instead of depositing silicon on the filaments.

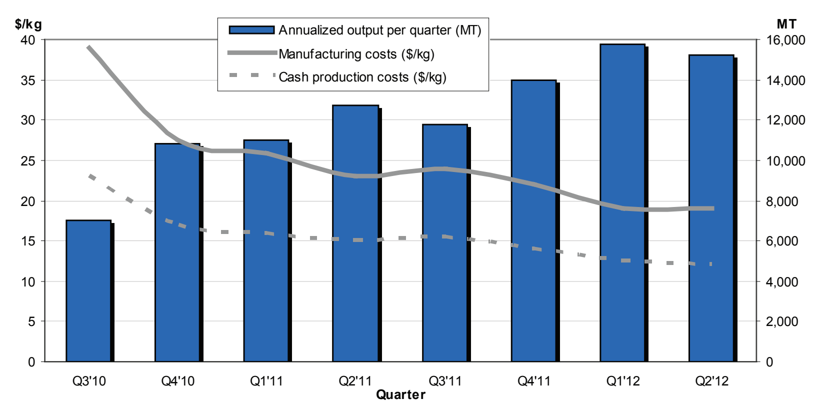
Schmid Silicon Technology GmbH (SST) has developed a way of reducing the rate of silicon dust formation below 2% and increasing the silicon deposition rate to 1 mm/h: details are discussed in Bernreuter [1]. SST's affiliate Schmid Polysilicon Production GmbH is running a semi-commercial plant in eastern Germany with an annual silane capacity of 540MT and a 180MT CVD reactor for test campaigns. For a 6000MT plant with an electricity rate of 0.08US$/kWh, SST projects manufacturing costs of $21/kg and cash costs of $13/kg.

At best, this would give the approach a slim cost edge over the Siemens process. Advantages are the high polysilicon purity of up to 11N and the marketable co-product silane. Lyle C. Winterton, an international silane expert who worked at UCC/ASiMI/REC for 25 years, regards Schmid's technology as the "best option in today's market", but he relativizes: "Monosilane CVD and TCS CVD have essentially the same cost." While silane avoids the complex vent-gas recovery of the Siemens process, its CVD is "much more difficult to run", says Winterton.

Silane in a fluidized bed reactor

As the announcement of GCL-Poly shows, the trend is towards CVD from silane in an FBR, in which tiny seed particles grow to polysilicon granules. Industry insiders say that a couple of other companies are working on silane-based FBR technology as well as GCL-Poly. Even Dow Corning Corp., which opened a 4000MT silane plant adjacent to the Michigan site of its polysilicon subsidiary Hemlock Semiconductor in August 2011, is reportedly considering bolstering its FBR research division.

The technology itself is not novel either. In 1987 Ethyl Corp. started up a silane-based FBR polysilicon plant in Pasadena, Texas, USA, which has been run by MEMC Electronic Materials, Inc. since 1995. Although FBR technology provides the advantage of very low energy consumption, the Pasadena plant cancels this out by Ethyl's expensive silane route, which applies the reduction of silicon tetrafluoride (SiF_4) with sodium aluminium hydride ($NaAlH_4$). The new 10,000MT FBR plant that MEMC is currently building in a joint venture



Sources: REC, Bernreuter Research estimates

Figure 2. Annualized output and manufacturing costs of REC Silicon's FBR plant in Moses Lake.

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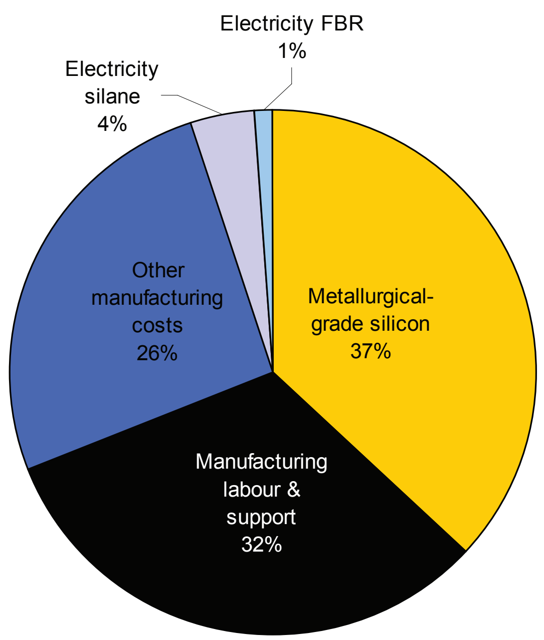

Source: REC

Figure 3. Breakdown of REC Silicon's FBR manufacturing costs.

with Samsung Fine Chemicals Co., Ltd. in South Korea will therefore use the disproportionation of TCS.

What has raised awareness of silane-based FBR technology is the progress that REC Silicon has made with its FBR plant in Moses Lake over the last two years. After start-up problems in 2009, the run rate has, remarkably, increased from the initial design capacity of 10,500MT to over 15,000MT in the first half of 2012. As a result, the manufacturing costs have dropped to $19/kg and the cash costs to $12/kg (Fig. 2).

> "REC presented a preliminary cost projection for an FBR plant in China with manufacturing costs of $11.3/kg and cash costs of $7.9/kg."

At the 6th SNEC PV Power Generation Conference in 2012, REC presented a preliminary cost projection for an FBR plant in China with very aggressive figures: manufacturing costs of $11.3/kg and cash costs of $7.9/kg [3]. Compared to REC's plant in Moses Lake, the capital expenditure is reduced by more than 50%, owing to both an optimized plant design and a local savings in China. Since electricity consumption cost only makes up 5% of the total manufacturing costs (Fig. 3), other savings mainly come from lower Chinese prices for labour and for the raw material metallurgical-grade silicon.

Looking towards the future: the push for high-efficiency cells

So far, one drawback to REC's polysilicon granules has been their high metal content, originating from the reactor wall. However, this contamination can be prevented by a removable liner. It requires a very sophisticated design such as that developed by MEMC. Indeed, in October, REC announced it is planning to introduce electronic-grade granules in 2013.

While a fifty–fifty mixture of granules and conventional chunks from polysilicon rods can shorten the time to fill a crucible by 40% and increase the charge weight by 30%, the particular value of granules lies in their being well suited to the continuous recharge of single crystal pullers working with the Czochralski (Cz) process. Continuous Cz technology promises both a better quality of crystal and a substantial cost reduction over the expensive batch Cz process. GTAT is aiming to introduce a continuous Cz system in 2013. This innovation has the potential to decisively promote monocrystalline high-efficiency cells, which have dominated the crystalline silicon section of EU PVSEC since 2011. The synergy between granular polysilicon and continuous Cz technologies could thus shape a powerful trend: perhaps in 2016, monocrystalline high-performance cells with efficiencies exceeding 22% will be more prevalent than many dare to imagine today.

> "Continuous Cz technology promises both a better quality of crystal and a substantial cost reduction over the expensive batch Cz process."

References

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About the Author

Johannes Bernreuter is head of the polysilicon market research firm Bernreuter Research, which he founded in 2008. Originally an associate editor for the PV magazine *Photon*, Johannes authored his first analysis of an upcoming polysilicon bottleneck and alternative production processes as early as 2001. He was awarded the prestigious RWTH Prize for Scientific Journalism by RWTH Aachen University.

Enquiries

Johannes Bernreuter
Bernreuter Research
Huttenstr. 10
97072 Würzburg
Germany
Tel: +49 931 784 77 81
Email: info@bernreuter.com
Website: www.bernreuter.com