INNOVATION IN SOLAR CELL PRODUCTION TECHNOLOGY

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ABSTRACT: A methodology for successful technology assessment is introduced. The comprehensive approach focuses on new techniques while looking at the process line on the whole, including questions of infrastructure, interfaces to other processes, handling, and material flow. Besides cost-of-ownership calculations, value of benefit analysis is a key tool to evaluate new ideas and technologies and the multidimensional assessment problem can be visualised by portfolio analysis, e.g. showing cost reduction potential versus realisation probability. Examples for innovative technologies under assessment right now are sputtering, in-line RTP, laser and plasma technology, and pad printing.
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1 INTRODUCTION

The strong growth of the solar business in the last years has recently reached a new stage: Almost every manufacturer in photovoltaics, whether producing wafers, solar cells or modules, announced plans of massive expansions in production capacity in the next year or two. A major factor to be taken into account for building new production lines is the permanent change of the boundary conditions, namely the trend towards thinner and larger wafers or ribbon materials and higher throughput and degree of automation. Every new PV production line is asked to meet these future requirements, not to mention the need of lower production costs coming along with increasing competition.

So there is a need for new but reliable technologies at low cost. New ideas and technologies emerge frequently and the story of solar cell processing is the story of improving solar cell concepts and techniques to meet the strong requirements of economical production. On the other side, production lines are not for testing, R&D resources are limited, and novel processes need to be well-elaborated and fully evaluated before implementing them into the line. The profound expertise in all areas of device physics, process and equipment technology, characterisation, and economical assessment together with an up-to-date knowledge of the market, as it now is concentrated at major international research institutes, is essential. Moreover, it is vital to follow a deliberate strategy to innovate solar cell production technology.

2 TECHNOLOGY ASSESSMENT

2.1 Methodology and tools

We use a comprehensive approach, i.e. focusing on new techniques but still looking at the process line on the whole, including questions of infrastructure, interfaces to other processes, handling, and material flow. Our methodology consists of six steps [1]:

(1) Analysis of the status quo including a technical and economical evaluation,
(2) survey of alternative technologies and ideas,
(3) assessment of the alternatives,
(4) critical experiments and simulations to explore the features and the suitability of novel technologies,
(5) conception of prototypes for testing, and
(6) final assessment and prioritisation.

Although it is straight forward, it is essential to really stick to the structure of the methodology in order to efficiently use R&D resources.

Obviously, innovation is an iterative process. That is why our methodology consists of feed-back loops between the individual steps: The outcome of one step is either starting point for the next step or input for another iteration loop through previous steps, often rejecting the investigated idea. However, if every step is comprehensively dealt with, the method is a short-cut for otherwise sometimes endless R&D activity.

Decisions within a technology assessment have to be based on quantitative and revisable facts. Therefore, a set of consistent rules and tools are needed to rate ideas. One, of course, is cost-of-ownership calculation, giving figures in Euro (or Dollars) per produced piece (wafer, solar cell, module, ...) and per Watt-Peak W_P. We have developed a cost-of-ownership tool considering different possible technology scenarios and which therefore allows "playing" with different options or boundary conditions.

Another important tool is a value benefit analysis. Here, an idea is rated in regard to several factors, like the technical efficiency, the possible production capacity, potential risks (technical and organisationally), the flexibility (e.g. in regard to different wafer sizes or to the use for other purposes or processes), the timeframe of a possible implementation, and necessary R&D efforts and expenses. To get a quantitative result, an idea to be assessed is given normalised "marks" in all these areas, usually by following fixed rules or by previously established mathematical functions of revisable figures like pieces, money, or time. The sum of the marks, weighted according to the importance of each factor, makes up the total value of benefit of a new idea or technology. The awarding of the marks, the weighting of the factors, and the factors themselves can be tailored to the specific situation of a company. However, in order to get a revisable result, the calculation in the value benefit analysis must not change during the assessment.

2.2 Cost-of-ownership and cost reduction potential

In principle, the cost-of-ownership is also part of the value benefit analysis, even though it is always listed separately also, since it is the familiar figure. It does not go directly into the analysis, but the cost reduction potential is considered, which is the sum of possible cost reductions due to increased efficiency, increased yield, and decreased process costs. The correlation between efficiency and cost reduction can be derived from the part of module costs that is related to the number of cells and modules and to installation area (~75%). The function describing cost reduction due to yield improvements takes material-related costs into account, including the issue of thinner wafers in cell processing (cost reduction due to material reduction versus possible yield reduction and higher handling costs) [1].

2.3 Portfolio analysis

With all the different factors or aspects, assessment is a multidimensional problem. The value benefit analysis leads to a single number, which can be ranked and compared to others. However, it is a good idea to keep the dimension of the analysis in mind. We therefore use portfolio analysis for detailed technology assessment and a basis for decisions within the assessment methodology [2,3]. In a portfolio analysis the rating of an idea is visualised as a function of two assessment factors or sets of factors, e.g. technical efficiency versus R&D efforts. If the two (sets of) factors represent all factors in the assessment, the value of benefit is visualised. We use a portfolio analysis where the value of benefit χ of an idea is represented as a function of cost reduction potential α and realisation probability β (which represents all other factors mentioned above):

$$\chi = \chi(\alpha, \beta) = 1 - \sqrt{\frac{(1-\alpha)^2 + (1-\beta)^2}{2}},$$

with α and β normalised and treated as equally important.

Introducing a lower boundary b (e.g. 0.3) and an upper boundary B (e.g. 0.7), there is a distinction of three cases (Fig. 1):

- $\chi > B$: Both, cost reduction potential and realisation probability are high; the idea should be realised.
- $b < \chi < B$: Cost reduction potential and realisation probability are moderate to high; the idea should be reviewed before realisation.
- $\chi < b$: Either cost reduction potential or realisation probability is very low or both are moderate to low; the idea should be rejected.

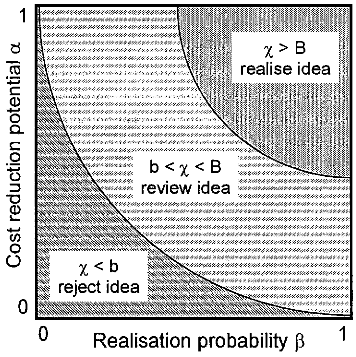


Fig. 1. Portfolio analysis for technology assessment. The ranking of an idea depends on its cost reduction potential and realisation probability, calculated within the value benefit analysis.

3 EXAMPLES

Examples for innovations in solar cell production technology currently under investigation are (i) sputtering, (ii) in-line RTP, (iii) the application of laser technology, (iv) plasma processing, and (v) pad printing. All these technologies have emerged from a survey of alternatives to improve coating, furnace processes, etching, structuring, or metalisation, respectively.

3.1 Sputter technology

Cost calculations and experiments show that sputtering has a huge potential as an alternative deposition technique in solar cell mass production. In Fig. 2 two particularly promising applications of sputtering SiN_x-films are positioned in the cost reduction potential versus realisation probability portfolio.

Sputtering of SiN_x as a mere AR coating is assessed with a good cost reduction potential due to:

- good optical properties
- high homogeneity on large surfaces
- low process costs for a high production volume

as demonstrated in an earlier publication [4]. Due to the great experience of similar coating equipment for the glass industry in combination with handling equipment already in use for in-line PECVD reactors, the realisation probability is assessed as being high.

The cost reduction potential further increases in the case of sputtered SiN_x films also featuring volume and surface passivation properties. The realisation probability is assessed as being medium to high since for these properties promising results have been reported but the evaluation phase has not been completed, yet.

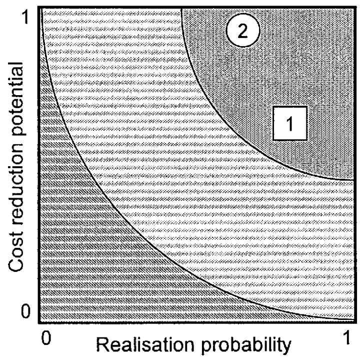


Fig. 2. Positioning of sputter technology in the portfolio: (1) Sputtering of a SiN_x AR coating, (2) sputtering of a passivating SiN_x AR coating.

3.2 In-line RTP

In-line RTP is already in an advanced stage of evaluation: Experiments show that RTP is well suited for solar cell processing leading to cell efficiencies up to 17.5% - 18% on industrial Cz-Si [5,6] and 16.7% on mc-Si [7], respectively, and that certain materials benefit from the low thermal budget involved [8]. Recently, also Rapid Thermal Firing (RTF) of screen printed contacts, i.e. contact firing using RTP, has been demonstrated to allow fill factors up to 80% [9-11]. So, all high temperature processes, for diffusion, oxidation, and contact firing, are developed to a stage, where the next step would be the transfer into production. The technology assessment is now in phase 5: An in-line RTP prototype [12] is currently under test (Fig. 3). Main feature is a novel transport system with low thermal mass that allows fast heating and cooling [13]. First solar cells on Cz-Si show up to 17.2% efficiency; the final assessment will provide detailed economic figures.

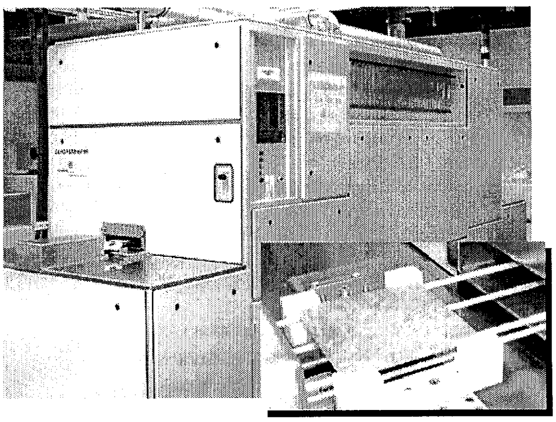


Fig. 3. Prototype of an in-line RTP furnace, currently under test. Main feature is a novel transport system with low thermal mass (inset).

3.3 Laser technology

There are several possible applications of laser technology in solar cell processing: The formation of grooves for buried grids [14] and edge isolation are processes already in use in production or easily to be integrated, respectively. Next generation silicon solar cells will include high efficient contact schemes like point back contacts used in Passivated Emitter and Rear Cells (PERC) [15] or interdigitated grids for emitter and base contacts on one side, and surface texturing. In all these areas the application of laser technology is under investigation and economical evaluation (Table 1). The processes are in different stages of assessment, already pointing to short-, medium-, and long-term potentials of laser technology in solar cell processing. While some applications require further development in laser technology, others are close to final assessment and implementation. As examples, different simplified PERC processes have been developed leading to lower cost high-efficiency solar cells with over 21% efficiency [16,17], and processes for edge isolation have been developed and are about to be implemented into an industrial-size prototype system [18].

Table 1. Process cost analysis of different applications of laser technology in solar cell production (uncertainty due to cost range of available laser systems).

Process	Cost (EUR-cent/W_P)
Edge isolation	0.2 - 0.4
Isolation or metalisation grooves for interdigitated grids	1.6 - 2.5
Ablation of contact holes for PERC back contacts	0.6 - 1.0
Grooves for buried grids	2.6 - 4.0
Surface texturing	2.0 - 3.1

3.4 Plasma technology

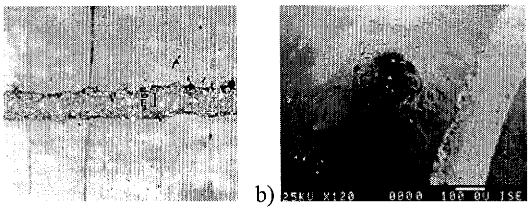
Plasma processing more and more quickens interests. While plasma deposition of silicon nitride (SiN_x) as antireflection coating (ARC) is already in use in some production lines, plasma etching processes, though, are well developed in the labs [19,20], but the implementation into production lines needs to be demonstrated. An appropriate survey and evaluation of plasma systems has been performed [21]. Now, plasma etching is at the transition from step 4 to step 5 of our methodology: The development of an industrial-scale prototype and last experiments necessary for its conception are under way.

Table 2. Survey of different plasma sources and evaluation of suitability for their use in solar cell processing.

Plasma Source	Etch Rates (μm/min)	Plasma damage	Processing area (cm^2)	Remarks
RF Parallel Plate	0.5-1	yes	limited to ~100	very common
MW Slot Antenna	0.5	no	limited to ~1,000	dc-bias possible
MW Linear Antenna	>10	no	unlimited	dc-bias possible
DC Atmospheric Downstream Plasma	>10	no	limited to ~10	no vacuum

3.5 Pad printing

Screen printing is the most common metallisation technique in industrial silicon solar cell production. However, with tightened requirements coming up, like finer lines for less shading losses, uneven substrates like ribbon materials, and thinner wafers, the limits of screen printing are in reach. From a survey of alternative metallisation techniques, one alternative found is pad printing [22,23]. It bears several advantages over screen printing, e.g. the possibility of fine-line printing down to several microns line width (Fig. 4a), good line definition even on uneven surfaces (Fig. 4b), and gentle printing on fragile materials [24].



a) b)

Fig. 4. Pad printed lines (a) of ~30 μm width and (b) with excellent line definition on uneven surfaces.

Pad printing is in an early stage of assessment: Preliminary technical results and economic figures are available. However, further R&D, especially the development of suitable metal pastes, is necessary.

4 CONCLUSION

A structured scientific approach to technology assessment has been established and demonstrated with several examples. It allows the stringent development of innovative techniques and to determine the time frame of their possible implementation into industrial production. Moreover, it minimizes economical risks and yields a highly efficient use of R&D resources.

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