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Potential of VHF-plasmas for low-cost production of a-Si : H solar cells

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Abstract

Compared to the use of the standard glow discharge technique the production of amorphous silicon solar cells by the very high frequency glow discharge (VHF-GD) bears yet additional cost reduction potentials:

Using VHF-GD at excitation frequencies higher than 13.56 MHz, a more efficient dissociation of silane gas is obtained; thus, higher deposition rates are achieved; this reduces considerably the deposition time for intrinsic amorphous and microcrystalline silicon layers.

Furthermore, by itself and even more so, in combination with argon dilution, VHF-GD technique improves silane utilisation and leads, thus, to further cost reduction.

Finally, by combining the VHF-GD technique and the "micromorph" concept "real" tandem cells (i.e. a superposition of two cells with distinctly different band gaps) can be deposited at low temperatures without the use of expensive germane gas.

Keywords: VHF-glow discharge; Plasma excitation frequency effects; Microcrystalline silicon; Argon dilution; Micromorph concept

1. Introduction

Experience from the past decade of research on photovoltaic energy conversion in connection with manufacturing of modules at pilot production level has brought the following statement to evidence: relatively expensive solar cells based on crystalline silicon wafers show high efficiencies; however, their cost reduction potential has

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already been almost fully exploited while using conventional techniques. On the other hand, thin-film solar cell concepts based on Copper Indium Diselenide (CIS), CdTe and on amorphous/microcrystalline silicon, have still a good cost reduction potential due to their large-area low-temperature ($T < 300°$) manufacturing possibilities; such a process technology leads to savings in the primary energy during the production and allows one to deposit on low-cost substrates.

A production analysis of the costs involved in the industrial fabrication of a-Si : H cells and related tandem cells shows that the following four factors are the main barriers to further cost reduction:

(1) TCO costs; (2) Substrate costs; (3) Turnaround time for the deposition of intrinsic silicon layers; (4) Silane costs (and even more so, the substantial germane costs, if Si/Si–Ge tandem cells are deposited).

In this paper we will show why the VHF-GD (very high frequency glow discharge) process introduced by our group is a process offering several striking economical advantages, coming, thus, close to the performance profile desired for producing low-cost thin-film silicon solar cells; we will also pinpoint the detailed physical differences between VHF-GD and the conventional (13.56 MHz) process.

2. VHF-plasmas and deposition rate

Turnaround time in cell production critically depends on deposition rates. Meanwhile, it has been shown by several groups [1–7] that an increase in plasma excitation frequency from the standard frequency of 13.56 MHz to values in the VHF range, e.g. 70 to 130 MHz, permits an increase in deposition rate by a factor of 4 to 10, both for a-Si : H as well as for μc-Si : H layers. The curves of deposition rate vs. excitation frequency (Fig. 1) usually show a maximum at a certain frequency and a decrease of deposition rate for higher frequencies: these features can be attributed to engineering aspects like reactor design. On the other hand, the generally observed increase in deposition rate with increasing excitation frequency can be attributed to fundamental physical changes in the capacitively coupled glow-discharge plasma.

The main physical change is a pronounced reduction of the sheath thickness which is related to a decrease in RF-voltage at the electrode; e.g. a dominant voltage drop of about 50 V [8] and an important decrease of the sheath thickness (see Fig. 2) of 2.2 to 1.4 mm is seen from plasma impedance measurements as the frequency is increased from 40 to 70 MHz [9]. Both observations are in agreement with other experimental and theoretical studies [10–12] and can be considered to be a general effect observed in VHF-plasmas.

As an important consequence of the thinner plasma sheaths and the lower RF-voltage (the latter being directly related to the sheath potential) a significantly better coupling of the RF-power into the bulk plasma rather than into the sheath can be obtained. Due to this, higher electron densities and better SiH_4 dissociation in the bulk plasma, as well as increased radical and ion flux onto the growing surface, can be achieved. A consequence of all this is a net increase in the deposition rate.

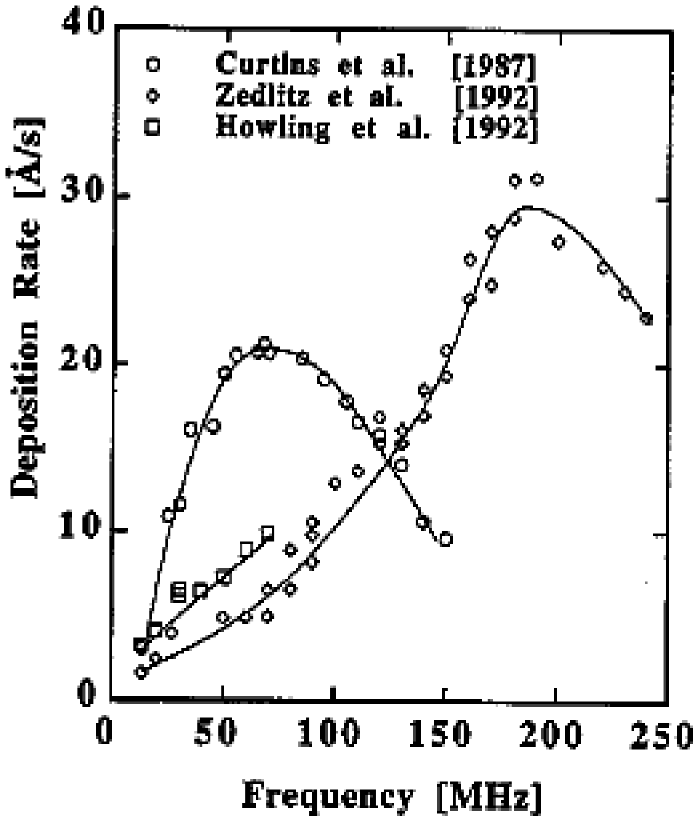

Fig. 1. Deposition rate vs. plasma excitation frequency, as obtained in different reactors and by independent research groups. Data taken from Refs. [1, 3, 4].

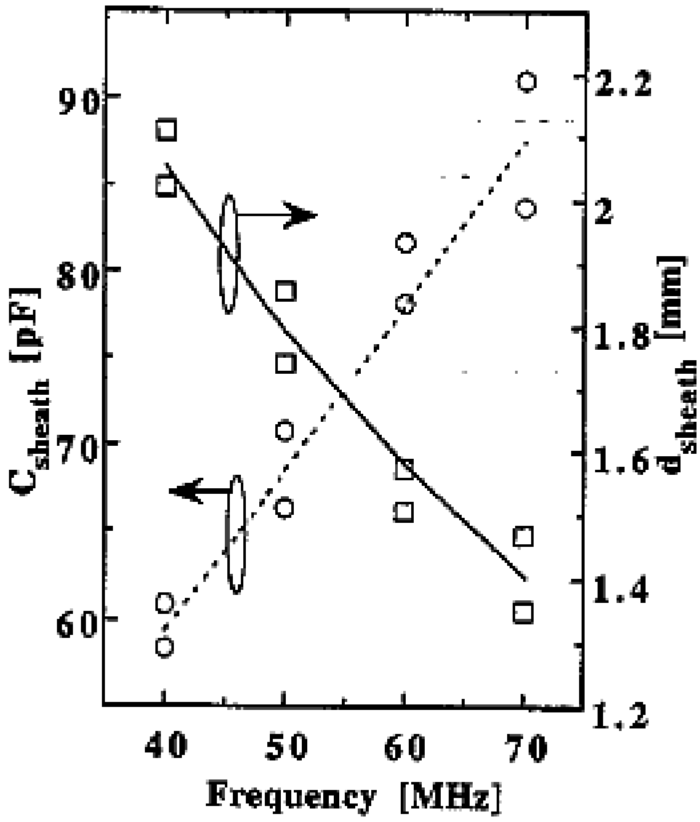

Fig. 2. Sheath-capacitance and corresponding calculated sheath-thickness of a hydrogen plasma vs. the plasma excitation frequency. Data taken from Ref. [9].

Strong experimental indications [4] for a higher dissociation of the silane in the bulk plasma can be obtained from a measured increase of the optical emission of the SiH*-line at higher frequencies while keeping the effective plasma power constant (see Fig. 3). It has to be noted that in pure silane plasmas the optical emission intensities of

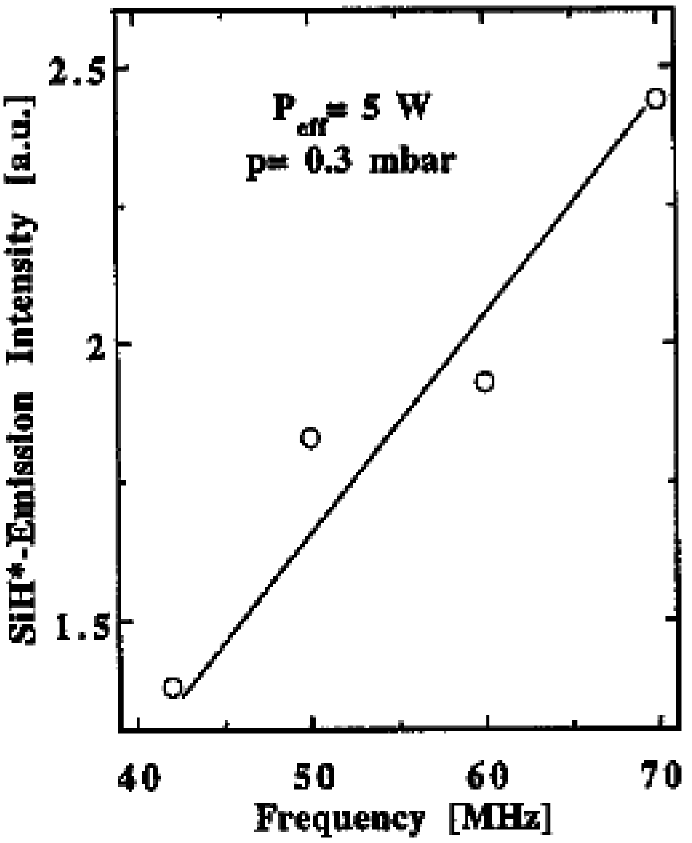

Fig. 3. Global optical SiH* plasma emission intensity at constant plasma power vs. the plasma excitation frequency. Data taken from Howling et al. [4].

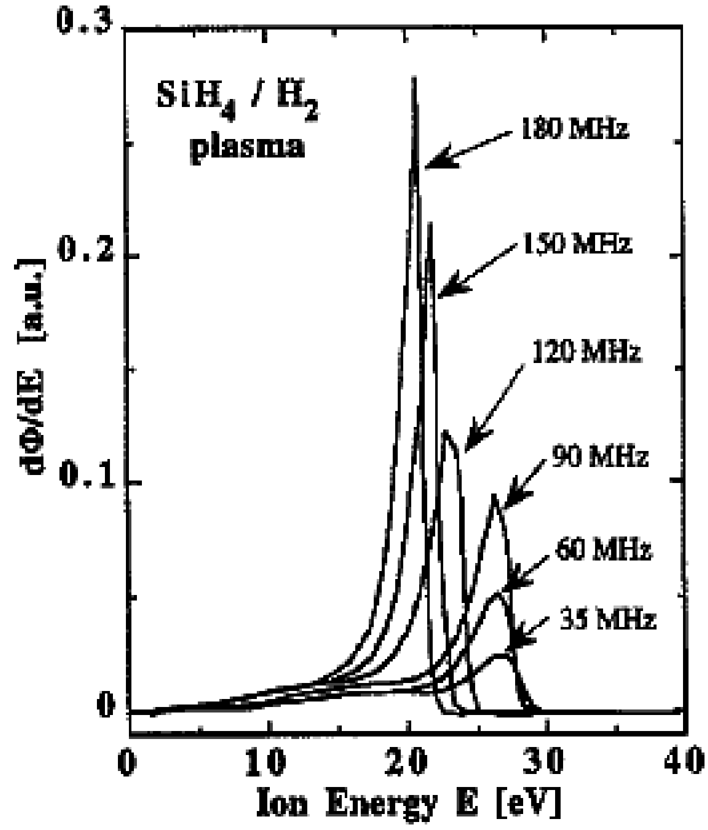

Fig. 4. Energy distribution of ions impinging on the substrate in a silane/hydrogen plasma for different plasma excitation frequencies. Data taken from Heintze et al. [15].

the SiH*-line represents a rough measure for the electron density [13, 14] present in the plasma.

Heintze et al. [15] measured an enhanced ion flux on the growth surface at higher frequencies (see Fig. 4) which is related to the changes in the bulk plasma and the sheath. They suggested that the enhanced ion flow to the growth surface could well be the growth-rate controlling mechanism in the deposition of the a-Si : H material due to an increased surface reactivity of the film precursors.

The reduced peak ion energy also observed is a direct consequence of the reduced sheath potential and might be a reason why VHF-plasmas favour microcrystalline growth.

3. VHF-plasmas using Ar-dilution

A surprising fact, observed in VHF-plasmas (see Fig. 5) is that when the silane feed gas is considerably diluted by Argon down to concentrations of about one-third the deposition rate drops by less than 10%.

Furthermore in this range of dilutions, the film properties do not deteriorate [8]; therefore, the consumption of silane feed gas can certainly be improved, by about a factor 3, by a combination of VHF plasma and Argon dilution; however, here, a detailed comparison with the 13.56 MHz standard PECVD has not yet been carried out.

It has recently been shown [16] that argon is not simply a buffer gas that reduces the secondary reaction probability between the radicals and the silane molecules, but plays an active part in the dissociation of silane via the argon metastable states present in argon-diluted silane plasmas.

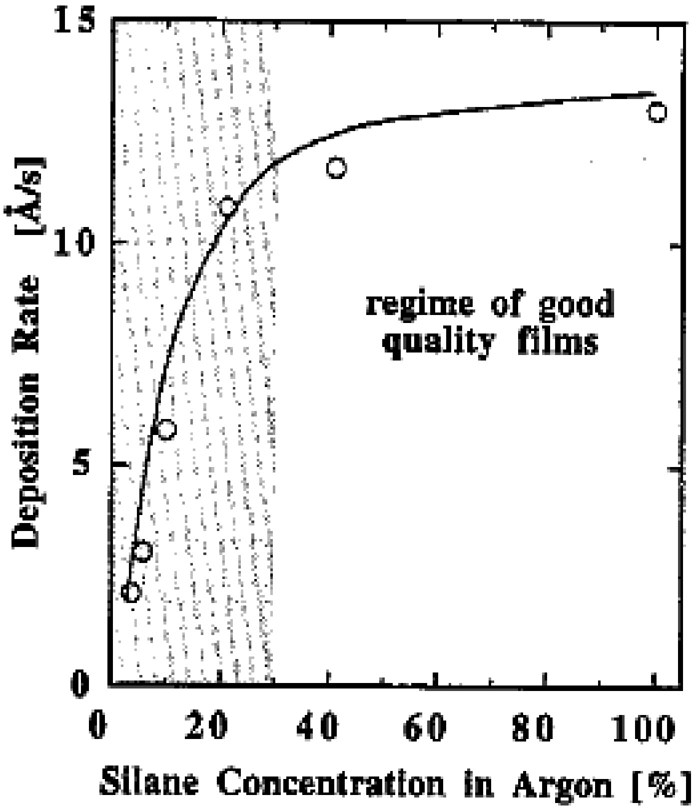

Fig. 5. Deposition rate of a-Si : H in VHF-plasma as a function of the silane concentration in Argon. Data taken from Ref. [8].

4. VHF-plasma and the "micromorph" concept

"Real" tandem cells ideally consist of the combination of a low and a high band gap material, making, thus, a better use of the full solar spectrum. If both materials involved can be deposited by the PECVD technique the advantage of a low overall production temperature (around 200°C) can be maintained.

A first pair of such semiconductors that are fully compatible with the PECVD deposition technique are a-Si : H and a-Si : Ge : H. However, one has here the disadvantage of having the need of the rather expensive germane feed gas. Furthermore, band gaps lower than 1.5 eV are difficult to obtain with a-Si : Ge:H alloys.

The VHF deposition process allows one to substitute the expensive a-Si : Ge : H layer by μc-Si:H material, which does not need germane for the deposition and, as a further advantage, shows no light-induced degradation. An unsolved problem is, for the moment, the long deposition times needed for the μc-Si : H bottom cells. The corresponding cell structure is shown schematically in Fig. 6. One can generally claim that the proven full technological compatibility between the μc-Si : H and the a-Si : H cell means that one has for such so-called "micromorph" cells [17] basically a similar cost reduction potential, as is generally expected for the a-Si : H.

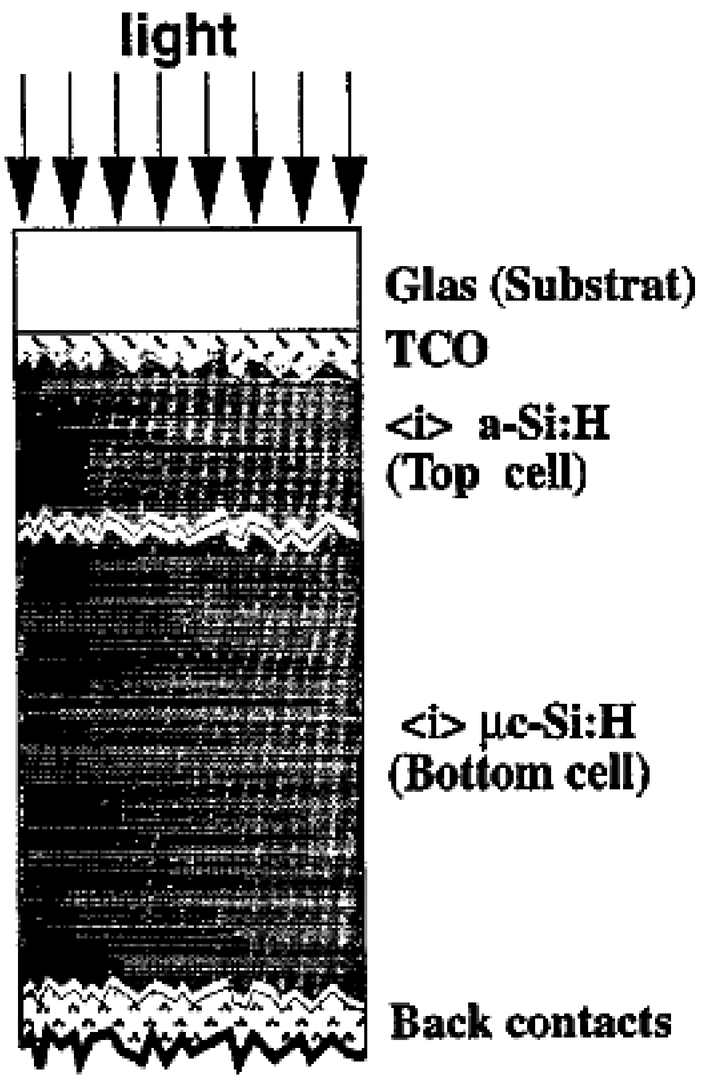

Fig. 6. Schematic cross-section of the a-Si : H/μc-Si : H "micromorph" tandem cell concept introduced by our group [17].

5. Summary

In contrast to high-temperature deposition processes the standard PECVD technique at low temperature as is generally used for the deposition of thin film a-Si : H films allows one to deposit on low cost substrates.

By applying the VHF-GD technique one obtains the following additional cost reduction capabilities:

(1) The high deposition rate observed in the VHF-process leads to a faster throughput for the deposition systems. It has been shown that this increase is dominantly induced by physical changes in the plasma.

(2) By a combination of VHF-GD and Argon dilution the silane dissociation in the gas phase can be additionally enhanced and thus improves silane economy. Certainly, by using this combination the silane consumption can be reduced by about a factor of 3.

(3) "Real" tandem cells bearing the basic potential for significant higher efficiencies when compared to single junction cells can now be realised by the "micromorph" concept as shown in a more detailed fashion elsewhere [18]. Thereby, the relatively expensive and unstable silicon-germane alloy is replaced by microcrystalline silicon. Therefore, a further cost reduction potential in the fabrication of "real" tandem cells is obtainable in this way.

In conclusion, we have pointed out several indications for significant cost reduction potentials in the a-Si : H cell production by the use of VHF-GD instead of the conventional GD technique at 13.56 MHz. The cost advantage of VHF-GD is even more striking when one compares the PECVD with high-temperature processes generally used to fabricate thin-film crystalline silicon.

Acknowledgements

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