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A new modular multichamber plasma enhanced chemical vapor deposition system

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The present work reports on a new modular UHV multichamber PECVD system with characteristics which prevent both the incorporation of residual impurities and cross contamination between different layers. A wide range of intrinsic and doped hydrogenated amorphous silicon (a-Si:H) materials have been produced and single junction pin solar cells with an efficiency greater than 10% have been readily obtained with little optimization. The system contains three UHV modular process zones (MPZ's); the MPZ's and a load lock chamber are located around a central isolation and transfer zone which contains the transport mechanism consisting of an arm with radial and linear movement. This configuration allows for introduction of the substrate into the MPZ's in any sequence so that any type of multilayer device can be produced. The interelectrode distance in the MPZ's can be adjusted between 1 and 5 cm. This has been found to be an important parameter in the optimisation of the deposition rate and of the uniformity. The multichamber concept also allows individually optimized deposition temperatures and interelectrode distances for the various layers. The system installed in Utrecht will be employed for further optimization of single junction solar cells and for research and development of stable a-Si:H tandem cells.

1. Introduction

The technique of plasma enhanced chemical vapor deposition (PECVD) is being increasingly used in the deposition of a wide range of thin films, such as amorphous semiconductors [1,2], nitride and oxide insulators and diamond-like carbon or diamond films.

The extensive work that has been carried out both in research laboratories and in industry on materials deposited by PECVD has resulted in the development of a wide range of PECVD systems with different features. The heart of any PECVD system consists in a vacuum chamber evacuated by a pumping unit to some appropriate vacuum level. The important figure of merit for any vacuum system, and for a plasma reactor in particular, is the total leak and degassing rate when the reactor is at deposition temperature: the ratio of this parameter to the process gas flow rate will largely determine the achievable purity of films deposited in that reactor. A good ultimate vacuum and therefore a low outgassing rate minimizes the in corporation in the deposited films of residual impurities such as oxygen, nitrogen and carbon, which can have a detrimental effect particularly on the properties of amorphous silicon. To this aim it is important to use an ultrahigh vacuum chamber with relative pumping system. Also in order to avoid all possible contaminations from the pumping system it is important to use a turbomolecular pump both during pumpdown and during process. All pumps must be purged by nitrogen to protect some of their most sensitive parts and to avoid possible accumulation of toxic or explosive components when reactive gases are used.

The independently variable parameters of the plasma deposition process in a particular reactor include the flow rate of the gases, the total pres-

sure of the gas, the interelectrode distance, the substrate temperature and the electrical excitation parameters such as power and frequency. A combination of appropriate values for these parameters has to be chosen in such a way as to obtain the desired film properties, such as film thickness uniformity, high deposition rate, good adhesion, good electrical and mechanical properties.

Many different reactor structures have been proposed to improve the quality of plasma deposited thin films and devices, in particular of those based on hydrogenated amorphous silicon. Reactors capable of depositing good quality materials should feature a good control by means of feedback loops of all the deposition parameters described above and should minimize contamination from all possible sources. For a UHV system to maintain a good base vacuum with as little contaminants as possible the process chamber should be vented to atmosphere as seldom as possible; for this purpose an additional load lock chamber is often used for the introduction of substrates. Cross contamination is a very important factor for the deposition of devices, since these consist of a few layers deposited from different gas mixtures: its effects may be detrimental especially in the case of boron and phosphorous in amorphous silicon, since a concentration of these dopants at the ppm level seriously degrades the photoelectrical properties of the intrinsic layer. Cross contamination effects are particularly severe in the case of reactor configurations in which different layers are deposited in the same chamber, due to outgassing from previous deposits on fixturing and chamber walls.

Reactor configurations with multiple chambers dedicated to processes to deposit layers with a specific gas mixture have been introduced to minimize cross contamination [3]; these usually consist of multiple reaction chambers configured in line, including entrance and exit load lock cham-

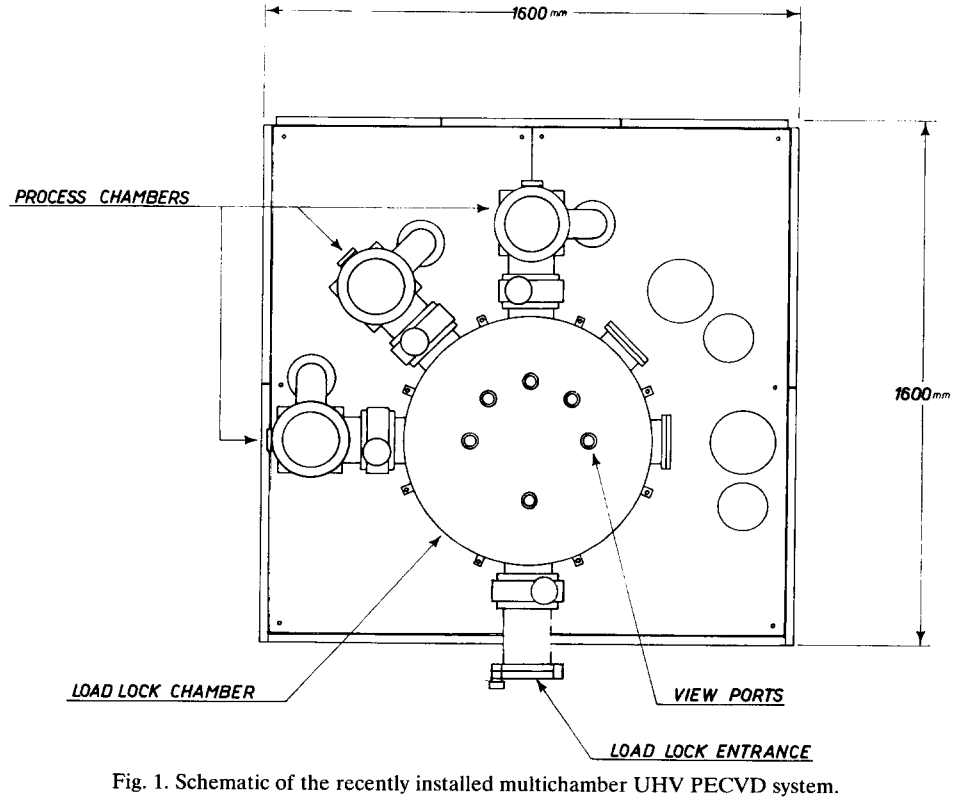

Fig. 1. Schematic of the recently installed multichamber UHV PECVD system.

bers. The present work reports on a new modular UHV multichamber PECVD system based on the cluster concept, allowing for greater flexibility in the development of multilayer structures.

2. Description of the system

The system contains up to seven modular UHV PECVD chambers of stainless steel construction (modular process zones or MPZ's) located around a central chamber which contains the transport system (isolation and transfer zone or ITZ); an additional load lock chamber allows introduction into the ITZ of the substrates (10 cm × 10 cm). The substrate carrier is moved by a transport arm which utilizes a vacuum compatible stepper motor for the linear movement; the arm rotates around a feedthrough placed in the center of the ITZ to position the substrate for introduction into the MPZ's. After the process the substrate is extracted from the MPZ and can be introduced into any other MPZ or taken into the load lock for unloading. The MPZ's and the load lock are separated from the ITZ by means of gate valves which are open only during substrate injection and extraction from the MPZ's and the load lock. An optimization of the mechanical setup of the transport system has allowed to achieve carrier transfer times between process chambers of less than two minutes. This configuration allows the deposition of layers in any sequence to produce any type of multilayer device, avoiding cross contamination between different layers. A schematic diagram of the system is shown in fig. 1.

The MPZ's are separately pumped using turbomolecular pumps and have separate gas manifolds; pumping of the process gas takes place via the turbomolecular pumps, which are equipped for use with corrosive gases. Each MPZ is complete with electrodes (anode and cathode), the distance between which can be internally altered from 1 to 5 cm. The substrate is facing downwards to avoid accumulation of dust particles. Each MPZ contains rails for transportation of substrates, an ionization gauge and associated display, a heater placed outside vacuum (to avoid contamination from this source) to heat the substrate by proximity, a type K thermocouple and associated controls, a capacitance manometer gauge head, a throttle valve and relative automatic pressure controller. The first MPZ is complete with a gas manifold with five mass flow controllers and associated control unit; the second and third MPZ's have their own gas manifold containing three and four mass flow controllers, respectively. A radio frequency generator (13.56 MHz) and an automatic matching network are switchable between the different MPZ's to enable the PECVD process to take place.

3. Experimental results

Intrinsic and doped hydrogenated amorphous silicon layers as well as p^+–i–n^+ solar cells have been deposited using the new modular multichamber UHV PECVD system installed at Utrecht University, obtaining materials and devices with state of the art characteristics [4]. The main material properties, such as dark and photo conductivity, optical energy gap and density of states (DOS) in the gap have been measured. The conductivities were measured using 500 nm thick layers and coplanar contacts. The absorption characteristics were determined by spectral reflection and transmission measurements. The deposition conditions for the single layers as well as for the solar cells are reported in table 1. Doped p-type layers deposited from the B_2H_6, CH_4, and SiH_4 gas mixture show a dark conductivity higher than 10^{-6} Ω^{-1} cm^{-1} and an optical energy gap

Table 1
Deposition conditions for layers of a-SiC:H/a-Si:H heterostructure p^+–i–n^+ solar cells

Parameter	Units	p-type	Intrinsic	n-type
SiH_4	sccm	20	40	40
CH_4	sccm	30	–	–
B_2H_6 [a]	sccm	5	–	–
PH_3 [a]	sccm	–	–	13
Pressure	mTorr	600	700	600
RF power	W	4	4	4
Heater temp.	°C	240	320	320
Depos. time	s	32	3300	180

[a] Dopant gases diluted at 2% in H_2.

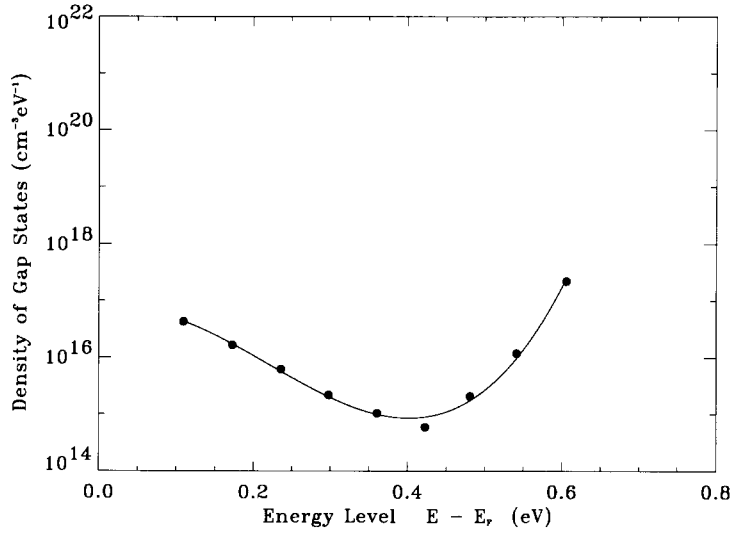

Fig. 2. Density of states distribution determined by TSC for an intrinsic a-Si:H layer of a quality used for solar cells.

of 1.95 eV; n-type doped layers deposited from the PH3 and SiH_4 gas mixture show a dark conductivity higher than 10^{-3} Ω^{-1} cm^{-1}. Intrinsic a-Si:H shows a dark conductivity in the 10^{-11} Ω^{-1} cm^{-1} range, and a photoconductivity under global AM1.5 illumination of 10^{-5} Ω^{-1} cm^{-1}. The density of states distribution in the gap has been determined by means of the thermally stimulated conductivity (TSC) method using a He cryostat [5]. Fig. 2 shows the energy distribution for the intrinsic a-Si:H layer employed in high efficiency solar cells. The density of states shows a minimum of 1×10^{15} cm^{-3} eV^{-1} which ensures a good minority carrier diffusion length.

Single junction solar cells were deposited using a conventional p^+–i–n^+ structure on SnO_2:F

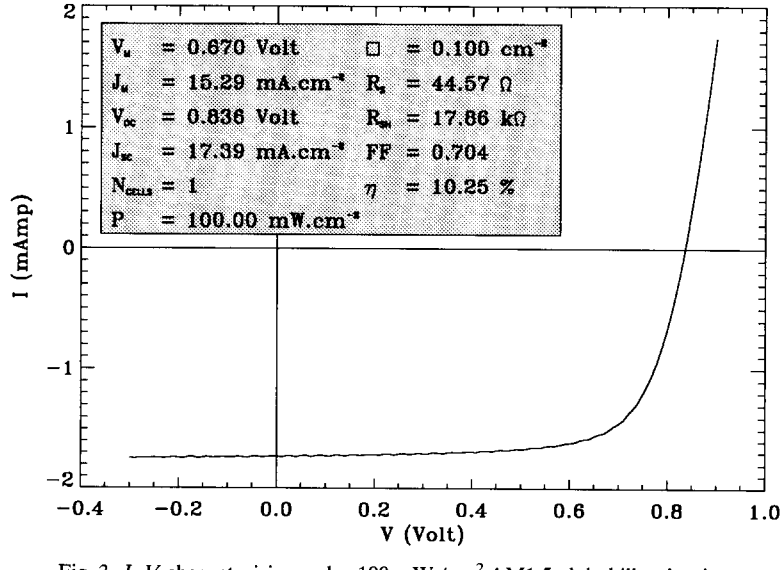

Fig. 3. *I–V* characterisics under 100 mW/cm^2 AM1.5 global illumination.

Table 2
Results of the performance of typical a-Si:H single junction cells over areas of 0.1 and 1 cm^2

Parameter	Units	Area	
		0.1 cm^2	1.0 cm^2
V_{oc}	V	0.84	0.84
J_{sc}	mA/cm^2	17.39	17.31
FF	–	0.704	0.670
η	%	10.3	9.7
FF (400 nm)	–	0.75	0.75
FF (600 nm)	–	0.76	0.76

textured transparent conductive oxide (20% haze). The structure was completed by evaporated Ag back contacts. The device efficiencies were measured under global AM1.5 (100 mW cm^{-2}) illumination both at Utrecht University and at the US National Renewable Energy Laboratory (NREL) in Colorado. Measurements at these laboratories were in agreement within experimental error and showed an efficiency of 10.3% for a 0.1 cm^2 device and 9.7% for a 1 cm^2 device. Fig. 3 shows the *I–V* characteristics. Table 2 reports data taken from these cells. It should be noted that the fill factor at the blue end of the spectrum (400 nm) is 0.76 which is one of the highest ever achieved and is indicative of good control of the p^+/i interface.

The solar cells were also analyzed using dynamic inner collection efficiency (DICE) [6] and they indeed showed complete collection from the 500 nm thick active layer. Fig. 4 shows the quantum efficiency data used for the analysis. These data were taken at various applied voltage biases using phase-sensitive detection of the spectral response under continuous white light bias. The high collection efficiency at small wavelengths is consistent with the observed high fill factor under blue light illumination.

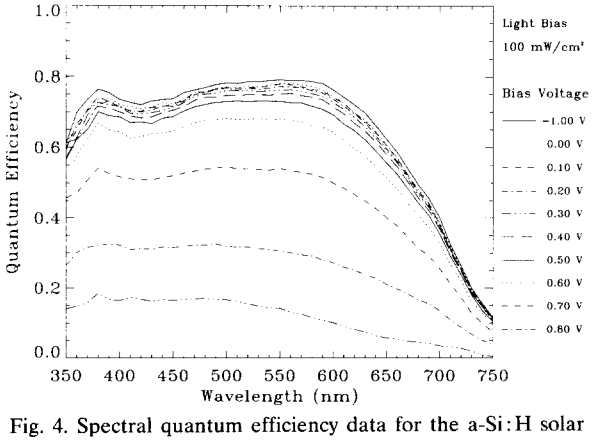

Fig. 4. Spectral quantum efficiency data for the a-Si:H solar cell.

4. Conclusions

A new UHV multichamber PECVD system consisting of multiple process chambers in a cluster configuration has been used to deposit single layers and devices of hydrogenated amorphous silicon. The system design prevents contamination from background impurities as well as cross contamination between different layers, allows deposition of multiple layers in any sequence and features the possibility to control a wide range of deposition parameters. State of the art materials and devices have been obtained with the system installed at the University of Utrecht.

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