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Amorphous silicon p–i–n diodes, deposited by the VHF-GD process: new experimental results.

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Abstract

a-Si:H i-layers were deposited at different substrate temperatures and plasma excitation frequencies, while the other deposition parameters were kept constant. These layers were characterised by measuring the intrinsic mechanical stress and the defect density. At deposition temperatures of 200 to 250°C low stress and a low defect density were obtained for excitation frequencies between 60 and 70 MHz. A second part shows the spectral response of thick p–i–n diodes for different reverse bias voltages. The data reveal a better collection efficiency for the case where generation of carriers is uniform throughout the i-layer, as compared to non-uniform generation, where carriers concentrate near the p–i interface.

1. Introduction

In the past three years, our group has presented several papers describing our research on thick p–i–n diodes [1,2]. Our aim was thereby to use these thick p–i–n diodes as particle or X-ray detectors. For these two specific applications, intrinsic layer thicknesses of 5 to 50 μm are required so as to obtain an acceptable sensitivity. The fabrication and utilisation of such thick p–i–n diodes presents several challenges: first, the adhesion and stress in the film has to be controlled to prevent the sample from peeling off; second, the deposition times are very long for thick films; we have previously shown [3] that they can be strongly decreased by utilising the high deposition rates achievable with the very high frequency (VHF) process. A further important factor that will be addressed in this paper, is the collection efficiency/spectral response of thick p–i–n diodes. The collection efficiency critically depends on the electric field profile, $E(x)$ within the i-layer. $E(x)$, on the other hand is strongly sensitive to the carrier generation profile.

2. Adhesion and stress

2.1. Experiment

The aim was to explore the intrinsic mechanical stress in an i-layer as a function of deposition temperature and of plasma excitation frequency. Both, the effective plasma power (4 W) determined by the 'substractive method' [4], as well as the pressure (0.3 mbar) were kept constant for all depositions. A series of i-layers, deposited on glass and crystalline Si wafers, were deposited by the VHF-GD process, with thicknesses ranging between 2.5 and 3 μm. The deposition temperature was varied between 150 and

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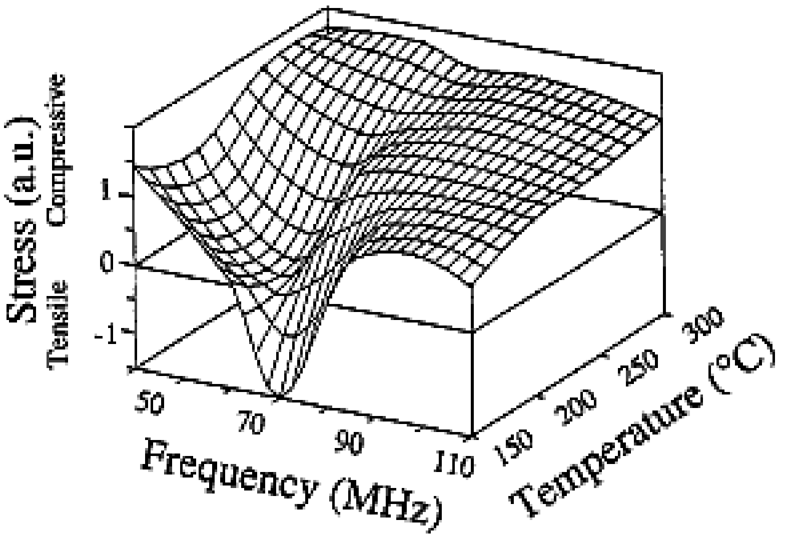

Fig. 1. Stress (in arbitrary units) as a function of plasma excitation frequency and deposition temperature.

300°C, and the excitation frequency between 40 and 110 MHz. In order to characterise the samples, the defect density was measured on the samples deposited on glass, with photothermal deflection spectroscopy (PDS), using the value of the absorption coefficient at 1.2 eV, multiplied by a calibration factor of 2×10^{16} cm^{-3} [5]. Mechanical stress was determined on the samples deposited on the wafer by measuring wafer curvature.

2.2. Results

The effect of excitation frequency and deposition temperature on the density of states and on mechanical stress are presented in Figs. 1 and 2. From this data, it can be concluded that the best samples (low defect density) have very often a high mechanical stress (sample deposited at 300°C); however, certain specific deposition conditions lead both to low stress and low defect density. A very interesting result is a pronounced dip in the three-dimensional stress plot as a function of excitation frequency and substrate temperature around 70 MHz and *at low temperatures.* Within this frequency range, samples even show tensile stress in the case of low deposition temperature.

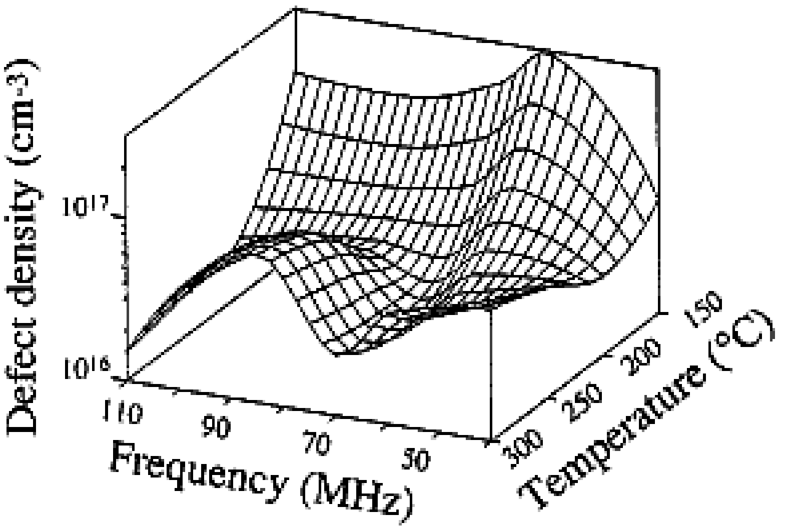

Fig. 2. Defect density, measured by PDS, as a function of plasma excitation frequency and deposition temperature.

2.3. Discussion

In order to explain the stress behaviour shown in Fig. 1, we assume that the reduction of mechanical stress at higher plasma excitation frequencies is due to a modification of the plasma characteristics. Thereby we distinguish three effects (1)–(3), listed here under.

1. At constant plasma power, the sheath potential (which governs the maximum ion energy at *lower* frequencies) decreases at higher excitation frequencies [6] and gives rise to reduced stress in the layers [7].
2. As the sheath thickness decreases at higher plasma excitation frequencies, but the mean free path of the energetic ions that impinge on the substrate is constant at constant pressure, less thermalisation of maximum ion energy due to ion neutral collisions occurs. As at excitation frequencies above 60 MHz only a slow further decrease of the sheath potential can be observed, this lack of thermalisation could explain the increase in the peak ion energy. This effect was modelled (for constant peak-to-peak voltages) by Surendra and Graves [8] and confirmed experimentally from ion energy measurements at constant plasma power by Howling et al. [11].
3. At excitation frequencies above 60 MHz, the sheath potential is more due to the plasma potential and less due to the peak-to-peak voltage. As shown in previous publications [9], the plasma impedance decreases at higher excitation frequencies, hence, the total discharge current increases at constant plasma power. As the total discharge current is proportional to the bulk electron density [4], an increase of the plasma potential for plamas driven at higher excitation frequencies will occur.

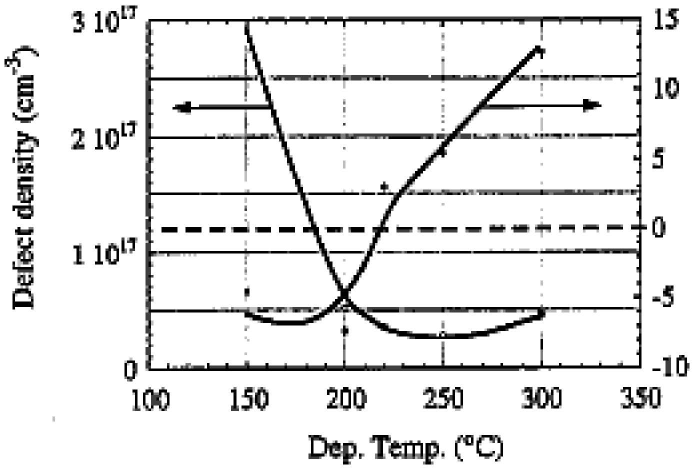

Fig. 3. Stress (in arbitrary units) and defect density as a function of deposition temperature for the samples deposited with a plasma excitation frequency of 60 MHz (negative means tensile stress).

Note that, here, the increase of peak ion energy is explained by an increase in plasma potential at higher excitation frequencies and not by reduced thermalisation as in (2).

The dip in stress observed at low substrate temperatures (Fig. 1) could be qualitatively due to effect (1) which leads to stress reduction; effect (1) competes either with effect (2) or effect (3) that both lead to stress increase. A final decision whether (2) or (3) is the predominant effect that leads to an increase in stress at frequencies above 70 MHz can not be given in this paper.

Looking at the stress at *higher substrate temperatures* as a function of the excitation frequency, no strong dependence was found. This may be due to the increased possibility for the atoms to rearrange at higher temperature, which, in turn results in a structure less dependent on ion bombardment. It is interesting to look in more detail at the results obtained for a plasma excitation frequency of 60 MHz (Fig. 3). From these results, one can conclude that samples with low defect density and no mechanical stress can be deposited at 60 MHz (for example, the sample deposited at 220°C has quite a low defect density (4×10^{16} cm^{-3}) and a very small compressive stress).

3. Thick p–i–n diodes

3.1. Results

Thick p–i–n diode are regularly deposited in our laboratory; the thickness of the i-layer can be varied from a few to 100 microns or more; to use such diodes as detectors, a good collection of the electron–holes pairs generated in the i-layer is required. All collection processes are dependent on the internal electric field distribution, which, in its turn, depends mainly on the reverse bias voltage, the defect density and the carrier generation profile (i.e. the wavelength). Fig. 4 presents spectral response measurements on a 16 μm diode: saturation of carrier collection appears at much lower reverse bias voltages in the case of weakly absorbed photons (red light: about 400 V) than in the case of strongly absorbed photons (blue light: more than 500 V).

3.2. Discussion

The results represented in Fig. 4 show that the internal electric field strongly depends on the wavelength of the incoming light:

1. if the incoming light on the ⟨p⟩ side is blue (strongly absorbed photons), the electric field becomes very low near the ⟨p⟩ layer, where the carriers are created;
2. if the incoming light is red, or infrared (weakly absorbed photons), the carrier generation will be more uniform in the i-layer, and the electric field distribution will tend to be more uniform.

This result agrees with the previous results published in [2], and with independent investigations finding a similar internal electric field behaviour for thin p–i–n solar cells [10]. A simple model, describing the electric field behaviour in a thick p–i–n diode is under consideration in our laboratory.

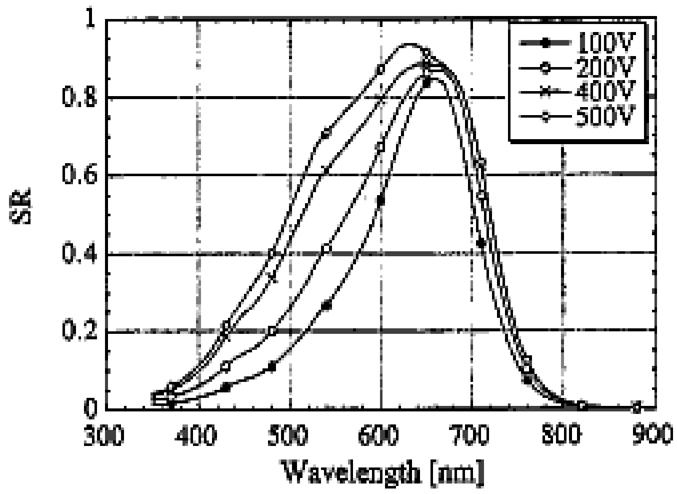

Fig. 4. Spectral response without bias light for p–i–n diode of 16 μm thickness and different reverse bias voltages.

4. Conclusions

The study of stress at different deposition temperatures and plasma excitation frequencies provide results of considerable practical relevance: we can observe that at certain deposition conditions one obtains layers with a low defect density, and, at the same time, a very low stress. This occurs at frequencies between 60 and 70 MHz, and deposition temperatures around 200°C. One can probably further optimise these deposition conditions to obtain even better results.

From the spectral response measurements, we have observed that the collection of carriers generated homogeneously in the whole i-layer saturates at lower reverse voltages than the collection of carriers generated near an interface. This means, that the collection of weakly absorbed photons (a situation that is comparable to X-ray or particle detection) is certainly better than the collection of carriers generated at the interface by strongly absorbed photons.

Acknowledgements

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