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HIGH-EFFICIENCY AMORPHOUS SILICON P-I-N SOLAR CELLS DEPOSITED FROM DISILANE AT RATES UP TO 2 NM/S USING VHF DISCHARGES

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Very high frequency (VHF) discharges (10–110 MHz) have been used to deposit high quality amorphous silicon at high deposition rates from disilane. The incorporation in p-i-n devices of intrinsic layers deposited at rates of up to 2 nm/s using 110 MHz discharges has resulted in the achievement of solar cell efficiencies greater than 9.5% over 1 cm^2 areas.

1. INTRODUCTION

Achieving high quality intrinsic a-Si:H films at high deposition rates is one important requirement for optimizing the production capacity of an a-Si:H solar module continuous production line. Disilane has shown promise as a means of achieving good material properties at high deposition rates. Furthermore, recent use of higher excitation frequencies (10–150 MHz) in silane discharges[1] has suggested that higher frequency may also be a means of achieving this goal. We have combined these two approaches and present here a summary of our key results of the effects of excitation frequency on disilane discharges, the properties of intrinsic a-Si:H, and the performance of p-i-n devices fabricated using intrinsic materials deposited at ~2 nm/s using 110 MHz disilane discharges.

2. EXPERIMENT

The deposition of a-Si:H films and devices were carried out in a commercially available GSI multichamber PECVD system. The rf power was supplied to the 130 cm^2 lower electrode by a variable frequency oscillator using a wide-band power amplifier. Materials were characterized by measurements of the dark and photoconductivity, the infrared (IR) absorption spectra, and the optical absorption. The hydrogen concentration C_H was determined for films deposited on crystalline silicon wafers from the integrated of the infrared absorption peak at ~2000 cm^{-1}. The fraction of $=SiH_2$ units f was determined from the deconvolution of the IR spectra in the 1900–2200 cm^{-1} region using Gaussian line shapes fitted to the absorption peaks at ~2000 cm^{-1} and ~2080 cm^{-1}. Apparent hole diffusion lengths under light bias L_l were measured by the surface photovoltage technique under 50 mW/cm^2 illumination. The density of defect states $g(E_F)$ was determined by the space-charge-limited current method. Devices were fabricated using glass/SnO_2:F/p/i/n/silver structures with 1 cm^2 opaque top contacts. The doped layers were deposited using 13.56 MHz discharges. The p layer used here was a wide band gap boron doped a-SiC:H layer. Device performance was measured under global AM1.5 (100 mW/cm^2) illumination conditions.

3. INFLUENCE OF EXCITATION FREQUENCY ON DISILANE DISCHARGES

The major effects of the driving frequency ω on the plasma are to decrease the operating pressure, increase the fraction of electrons in the high energy tail of the electron energy distribution, increase the electron density, and reduce the plasma potential. The reduction in the operating

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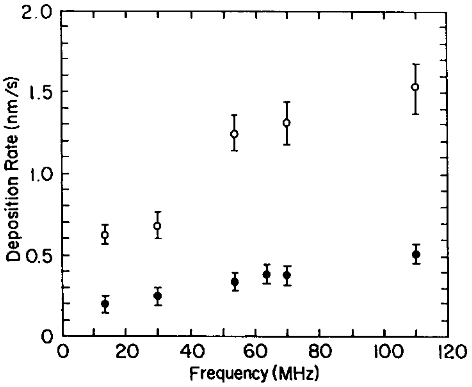

Figure 1
The deposition rate as a function of discharge excitation frequency for films deposited from silane (0) and disilane (0) at a power density of 31 mW/cm^3.

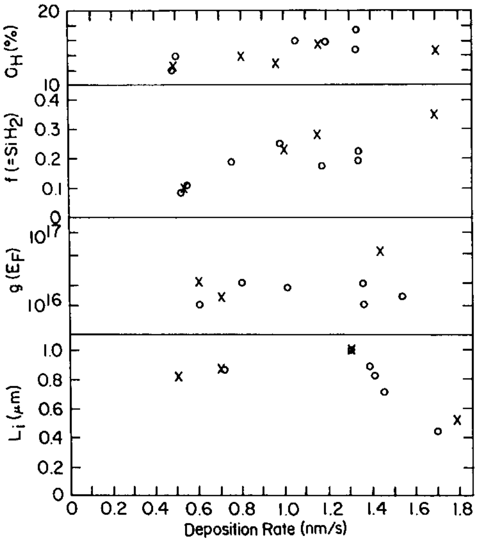

Figure 2
The properties of films deposited from disilane as a function of deposition rate. Open circles refer to materials prepared at 31 mW/cm^3 at various excitation frequencies and the crosses refer to materials deposited at 13.56 MHz at various rf power densities.

pressure (from ~0.39 Torr at 13.56 MHz to 0.05–0.08 Torr at 110 MHz) results in a decrease in the rate of gas phase reactions leading to polymerization, hence in the densities of large species. However, due to the scaling of the sheath thickness d_s with frequency and gas density N, the sheath thickness remains approximately constant ($d_s \sim 1/N\omega$).^{2} Under these conditions, the probability of a radical specie reacting before reaching the substrate decreases with decreasing pressure.^{3} Therefore, the contribution to deposition by the more reactive radical species increases with increasing discharge excitation frequency. The increased fraction of electrons in the high energy tail of the electron energy distribution and the increase in the electron density are consequences of the increased coupling of energy from the applied field to electrons in the high energy tail with increasing frequency.^{4} The changes in the electron kinetics result in increased dissociation and deposition rates. The deposition rate increases as shown in Fig. 1.

Another important effect of the driving frequency is to decrease the plasma potential. In disilane at a power density of 31 mW/cm^3 the plasma potential drops from ~26 V at 13.56 MHz to ~5 V at 110 MHz. This change causes a corresponding drop in the maximum ion bombardment energy at the substrate surface. However, the ion flux follows the increase in the electron density with increasing frequency. The larger flux of low energy ions to the surface at 110 MHZ should promote surface diffusion, which results in higher quality films than at lower frequency.

4. THE INFLUENCE OF EXCITATION FREQUENCY ON THE PROPERTIES OF MATERIALS DEPOSITED FROM DISILANE

We summarize the most important effects we have observed in Fig. 2. In general, the effect of frequency on the material properties of films deposited from disilane is similar to the effect of rf power at 13.56 MHz: the light and dark conductivity decrease, and the hydrogen content and the amount of hydrogen

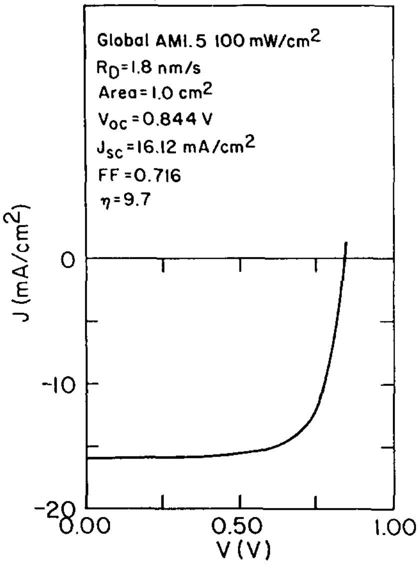

Figure 3
The performance of a 1 cm^2 p-i-n device fabricated using an intrinsic layer deposited from disilane at a rate of 1.8 nm/s

bonded in the dihydride configuration increase with increasing deposition rate. However, the density of localized states remains approximately constant. Furthermore, the fraction of hydrogen bonded in the dihydride configuration is lower at high deposition rates (~1.7 nm/s) at 110 MHz than at high rf power density at 13.56 MHz. The similarity between the effect of rf power density and excitation frequency on the properties of materials suggests that the deposition rate itself has a larger influence on the properties than does the method of increasing the deposition rate. This suggests that the competition between the surface diffusion rate and the deposition rate controls film properties. Thus in order to improve the properties of materials deposited at high deposition rates, the surface diffusion rate must be increased. We speculate that the reduction in the dihydride content in films deposited at 110 MHz compared with those deposited at 13.56 MHz at the same deposition rate is associated with increases in the surface mobilities due to the increased flux of low energy ions.

5. DEVICES FABRICATED AT 110 MHz.

The performance of devices fabricated using intrinsic layers deposited from disilane at rates of ~2 nm/s using 13.56 MHz and 110 MHz discharges indicates that the use of the higher frequency results in significant superiority of device performance. The improvement is associated with increases in the fill factor and the short circuit current density. As a result, we have achieved efficiencies exceeding 9.5% over 1 cm^2 areas using disilane (See Fig. 3).

6. CONCLUSIONS

We have fabricated devices with efficiencies > 9.5% over 1 cm^2 at deposition rates approaching 2 nm/s, thus demonstrating that disilane can be used to fabricate high efficiency devices at high deposition rates. These are to our knowledge the highest efficiencies achieved for devices with areas 1 cm^2 at these deposition rates. Finally, a comparison of the influence of rf power and discharge excitation on properties indicates that the deterioration of properties is roughly independent of the method of increasing the deposition rate. Thus the deposition rate itself is a major determinant of film properties.

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