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Title of Thesis: Fabrication of Diffused Junction Crystalline Silicon Solar Cells with Texturization and Different Antireflection Coatings and Study of their Photovoltaic Properties

Abstract of the Ph.D. Thesis

During the course work n^+-p single crystalline and multi crystalline silicon solar cells were fabricated by carrying out the diffusion of phosphorous impurity into p-silicon wafers of ~ 1 Ω-cm resistivity at ~ 880^0C for 15 min using $POCl_3$ as a liquid dopant source of phosphorous. Single crystalline solar cells were made from <100> oriented c-Si wafers which were textured in a hot NaOH solution before fabrication of the n^+-p junction, whereas, the multicrystalline silicon solar cells were made using mc-Si wafers which were subjected to acid texturization in a mixture of HF and HNO_3 and D.I. water before junction fabrication. Thereafter, a single layer silicon nitride (SiN) anti reflection coating of thickness nearly 80 nm was applied by a plasma enhanced chemical vapour deposition (PECVD) process using SiH_4, NH_3 and N_2 gases. Front metal contact was made by screen printing Ag paste in form of a grid pattern that covered ~10% of the area on the front surface, whereas, the back contact was made by screen printing a Ag-Al paste on the whole back surface. Both contacts were sintered simultaneously at ~700C for 2min in air ambient.

The above cells were characterized using I-V and Spectral response techniques etc. and were then used for carrying out investigations that led to the development of a new method for determination of diode parameters of solar cells. This is an analytical method that determines all the four diode parameters of a solar cell based on single diode model from the variation of slopes of the I-V curves of the solar cell near short circuit and open circuit conditions with intensity of illumination P_{in}. In a suitable range of intensity the slope (dI/dV) at short circuit enables determination of R_{sh}, whereas, the variation of slope (dI/dV) at open circuit with P_{in} enables determination of R_s, n and I_0. The diode parameters of c-Si and mc-Si solar cells were determined with this method using I-V characteristics of the cells in 40-125mW/cm^2 intensity range of a simulated AM1.5G solar radiation. Theoretical I-V curves generated using so determined values of the diode parameters matched well with the experimental I-V curves of the cell obtained under various intensities of illumination in the above range. This method is superior to other methods which determine one ore more diode parameters of solar cells. It has also been applied successfully to silicon solar cells of Mette et al and PV modules of Cueto, and CIGS solar cells of Marlein & Burgelman.

The effect of illumination intensity P_{in} on the diode parameters of a silicon solar cell has also been investigated based on the above method of measurement of diode parameters. The dependence of diode parameters of the silicon solar cell on intensity has been investigated for a fairly wide illumination intensity range 15-180 mW/cm^2 of AM1.5 solar radiations by dividing this intensity range into a desirable number of small intensity ranges for measurements of the slopes of the I-V curves at short circuit and open circuit conditions. It has been found that initially R_{sh} increases slightly with P_{in} and then becomes constant at higher P_{in} values. However, R_s, I_0 and n all decrease continuously with P_{in} but the rate of decrease of each of these becomes smaller at higher P_{in} values. Theoretical values of V_{oc}, CF and η calculated using the cell parameters determined by the present method match well with the corresponding experimental values.

More than 34% of the incident band gap light is reflected from the chemically polished surface of silicon. This reflection loss can be reduced by texturization of front surface or application of antireflection coating on the front surface of the solar cell. The recombination at the surfaces is more than the recombination in the bulk of the semiconductor materials. So, the recombination loss can be reduced by applying passivating layers on the front and back surfaces of solar cells. In the course of present work the usefulness of Al doped ZnO films in reducing the reflection losses and surface recombination losses has been investigated. For this purpose the Al doped zinc oxide (AZO)

thin films of Al/Zn atomic ratio in 0-40% were prepared by Sol gel process and their structural, optical and electronic properties were studied. The studied of AZO films with 20% Al-Zn ratio (for convenience referred to as 20% AZO films) were studied in greater details

Solutions for synthesis of AZO films were prepared in ethanol using zinc acetate dihydrate and aluminum nitrate nonahydrate in different molar ratios. A small amount of diethanolamine (DEA) was added as stabilizer to clear the solution. The 5:1 molar ratio of zinc acetate dihydrate and aluminum nitrate nonahydrate gave Al doped zinc oxide (AZO) thin films with Al/Zn 20% atomic ratio. These films were initially dried in air in an oven at 200^0C and, then, the samples were heat treated separately at a constant temperature between 300-600^0C in air or hydrogen ambient for 30 min to study the effect of ambient on the structural, optical and electronic properties of the films [9]. All the 20% AZO films annealed in the above temperature range were found to be crystalline possessing characteristic ZnO wurtzite structure.

The refractive index and thickness of the 20% AZO films coated on chemically mechanically polished FZ silicon wafers were measured at 632.8 nm wavelength (λ) with an ellipsometer, Garter model L117. The refractive index of the 20% AZO films heat treated in the above temperature range are suitable for antireflection coating to the silicon solar cells. The minority carrier lifetime in FZ silicon wafers coated with 20%AZO films was measured using microwave photoconductive decay (μ-PCD) technique, wherein, the 20%AZO films were annealed in air or hydrogen ambient. After annealing of 20%AZO coated silicon wafer in hydrogen ambient for 30 min between 400-600˚C the effective minority carrier lifetime τ_{eff} improved above the initial value of ~16μs and attained a maximal value of ~71µs for annealing at 500˚C. It was because above 400˚C the molecular hydrogen gets dissociated into atomic hydrogen in presence of Al induced defects at the AZO coated silicon surface and passivates them by formation of Si-H-Al complex. The annealing in air in the same temperature range did not affect the lifetime. The 20%AZO films annealed at 500˚C in hydrogen or air show high transmittance in 400-1200 nm wavelength range and are suitable as AR coating for silicon solar cells.

Fourier transform infrared (FTIR) spectra of 20%AZO films coated on silicon which were recorded in transmission mode exhibited increased Si-H_3 bonding in 20%AZO film annealed in hydrogen at 500C for 30min. This should be responsible for defect passivation and the observed increase in the effective minority carrier lifetime of the 20%AZO coated silicon wafers after annealing in hydrogen. For studying the effectiveness of 20%AZO films as antireflection coating and passivation layers to silicon solar cells hydrogen annealed 20%AZO film of appropriate optical thickness were applied on n^+ front surfaces and equally thick hydrogen annealed 20%AZO coating on the p-back surfaces of a few n^+-p structured mono- and multi-crystalline bifacial silicon solar cells. The coatings were annealed simultaneously at 500C for 30 min in hydrogen. The observed improvement in J_{sc}, V_{oc} values of the cells established that the while 20%AZO film on front acted as a good AR coating the 20%AZO film on the back surface passivated the back surface effectively.

The front and back illuminated internal quantum efficiencies of a mc-Si bifacial cell were measured in the wavelength range 300-1200 nm. The value of diffusion length determined from the internal quantum efficiency of the cell in 900-1050 nm wavelength range was found to have increased to ~254μm from its initial value of ~60μm. This confirmed that there was a significant improvement in the performance of the bifacial solar cell due to the passivation of the back surface.

Further an attempt has been made to see the effect of Al/Zn atomic ratios (in 0-40 % range) AZO films annealed at 500C in hydrogen ambient on the optical, structural and electronic properties of the films. The effective minority carrier lifetime of a FZ-Si wafer increased with increase in Al/Zn atomic ratio of AZO coating and attained a maximal value of ~52 μs for Al doping concentration of 30% from its initial value of 11 μs for uncoated silicon wafers. The effective minority carrier lifetime τ_{eff} starts decreasing for Al/Zn ratio above 30%. Thus our investigations reveal that a sol-gel derived 20-40% AZO film annealed at 500C in hydrogen is quite suitable for use as an antireflection coating on n^+ front surface and as a passivating layer on the p-back surface of an n^+-p silicon solar cell.