New approaches for extremely high doping and high crystal fraction in the mixed phase nano-crystal silicon thin film by near room temperature deposition process with neutral beam assisted CVD; Transition of transport path and lateral grain growth.

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Abstract

In order to apply various portable devices lightweight forms, such flexible solar panels, fabrication require very low temperature (or near room temperature) processes. Various methods, such as capacitively coupled RF-PECVD, hot wire CVD, very high-frequency PECVD and electron cyclotron resonance CVD have been extensively used for the fabrication of nc-Si thin films. Nevertheless, how to simultaneously obtain high-quality nc-Si thin films at low temperature for flexible device applications still remains a competitive challenge in the existing fabrication techniques. Moreover, it is generally processed that high dilution of reactant gases with H is an essential requirement for the formation of nc-Si thin films. A nano-crystalline (nc)-Si thin film is more stable but possesses lower absorption in comparison to an a-Si thin film for Si thin film based solar cell. For overcoming the weakness of the a-Si:H and nc-Si:H thin film, “nc embedded polymorphous(pm) silicon (nce-p-Si)” is considered as one of alternate. These nc-Si related phases have higher stability than amorphous and higher absorption coefficient than micro-crystal (μc) or nc phases. Additionally, high H diluted nc-Si thin film solar cell is hardly free from an incubation layer issue, similar with μc-Si, that causes high series resistance, low shunt resistance between the inter layers. Another issue of flexible device is how to deposit and activate a doped thin film at low temperature because doping process always need high temperature process or post annealing for electrical activation.

Recently, we are developing a novel CVD technology with a neutral particle beam (NPB) source, named as neutral beam assisted CVD (NBaCVD), which controls the energy of incident neutral particles (mainly H and Ar) in order to enhance the atomic activation and crystalline of thin films at near room temperatures (<80°C). In traditional hydrogenated Si deposition, the gas mixture ratio of H and Si controls the phase of thin films, such as a-Si:H, μc(or nc)-Si:H, while the substrate temperature determines the doping efficiency, mainly. Conversely, the NBaCVD system can control the crystalline phase and the doping efficiency simultaneously by the energy of impinge neutral particles. During the deposition process, energetic H-neutral atoms transport their energy to the surface of depositing film to enhance crystallization (crystal volume fraction (Xc) ~85%) and dopant activation (~1X10^{20} #/cm^3, ~30 cm^2/Vs) with low H ratio at near room temperature on the substrate. Also the increase of H enhance transport path (mobility incensement) which is deduced from transition of crystal orientation from [111] to [311] at constant Xc. The various analysis data of the thin films (XRD, Raman, temperature dependent conductivity, Hall measurement) represent the evidence of very high doping efficiency at near room temperature, obvious nc embedded pm phase, and mixed transport (band and percolation) characteristics.

Figures

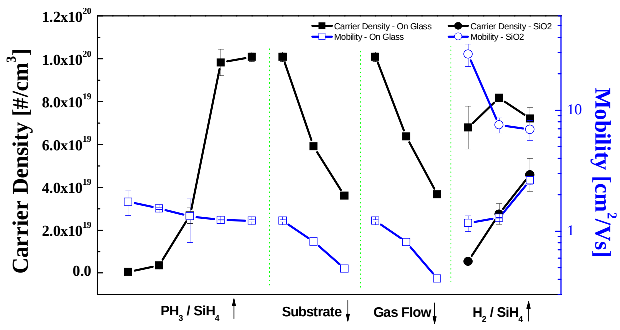

Figure 1. Carrier density and mobility properties of low temperature deposited nano-crystal silicon thin film

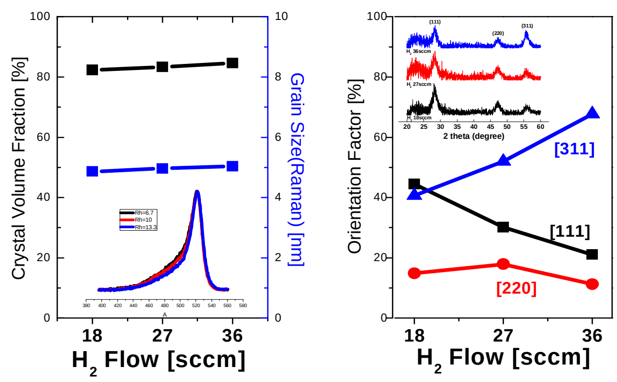

Figure 2. Ranm and XRD analysis: hydrogen flow rate dependent NB effect of nano-crystal structure

From Figure 1, the best doping concentration achieved by using NBaCVD is 10^{20} #/cm^3. Conventional PECVD and ion implantation method need post annealing process over 650°C to achieve this high doping level. The theoretical maximum dopant solubility is around 4*10^{20}~10^{21} #/cm^3. Substrate temperature dependent thermal dopant activation does not apply to NBaCVD deposition process because the process was maintained lower than 80°C. The achievement of high doping at low temperature process indicates that the activation is mainly dependent on the energy of NB.

From the Raman spectra (Figure 2, lfet), the crystal volume fraction and mean grain size remain unaffected as gas ratio (PH_3/SiH_4, 0.86~10%), R_H(H_2/SiH_4, 5~10). This Raman properties is compared with conventional PECVD process which is influenced by gas ratio dominantly. The crystal nucleation and grain growth depend on HNB. And the XRD results (Figure 2, right) provide the orientation transition from [111] to [311] as increase of hydrogen flow. In μc-Si which of grain grow mainly vertical direction with [111] orientation, the vertical charge transport is higher than lateral transport. However NBaCVD processed nc-Si thin film show [311] orientation transform and enhance mobility as increase of hydrogen flow.

Recently, we measured the temperature dependent conductivity that represent mixed transport of percolation and phonon assisted band transport and GIWAXS that represents transition of lateral grown grain orientation as neutral beam energy.