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Persistent photoconductivity studies in a-Si:H/nc-Si:H thin film superlattices

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ABSTRACT

The electronic properties of undoped a-Si:H/nc-Si:H superlattice structures have been investigated by photoconductivity measurements. Multilayer structures having alternate layers of a-Si:H and nc-Si:H were deposited on corning 1737 glass substrate by Hot wire chemical vapor deposition technique, keeping the total thickness of films constant at 700 nm. Dark and photo conductivity along with persistent photoconductivity (PPC) are measured in coplanar geometry using Ag paste as electrodes. Quite interestingly room temperature PPC has been observed in these undoped a-Si:H/nc-Si:H superlattice structures. PPC decay time constant, its dependence on exposure time, electric field, number of periods and annealing temperature have been studied in detail. The origin of PPC is understood in terms of competition between carriers transport in the lateral direction due to external field and along the depth due to band bending at a-Si:H/nc-Si:H interfaces. Carriers trapped in the interfaces states or the separation of carriers due to band bending are likely to be responsible for observed PPC.

1. Introduction

It is well established by now that among the various semiconductor thin films, hydrogenated amorphous (a-Si:H) and nanocrystalline silicon (nc-Si:H) films have much more potential for fabrication of large area thin films based solar cell and other optoelectronics devices [1,2]. The disorder in a-Si:H material, which results in defects that act as recombination centers impending the transport of photo-generated carrier is the major drawback of a-Si:H thin films. In recent years, nc-Si:H thin film have attracted considerable attention because of their superior electronic properties compared to a-Si:H along with better stability. The major challenge in this technology is the improvement of solar cell efficiency. Multi-junction structures with component cells using different band gaps have been used to capture a wider spectrum and hence improve the cell efficiency [3,4].

A new class of materials prepared by depositing alternate layer of thin films of amorphous and nano-crystalline silicon, that is, the superlattice structure of a-Si:H/nc-Si:H, show many interesting features such as stable photoluminescence and enhanced vertical photosensitivity [5–7]. Superlattice structures based on amorphous layers have also been proposed as novel transistors [8], in which a superlattice of alternating low and high-band gap layers comprises the channel region between the source and drain of a thin film transistor. Such superlattice structure was proposed to offer considerably higher performance and mobility than typical a-Si:H thin film transistors [8]. The photonic and plasmonic enhancement in a-Si:H

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and nc-Si:H thin films have previously been reported by several groups [9–11]. Very recently, Pattnaik et al. [12] measured a large photo current enhancement in (a-Si:H/nc-Si:H) superlattice based solar cells. Even thermal transport properties of these structures were investigated and studied. It was found that thermal conductivity of superlattice structure was $2\ W\ m^{-1}\ K^{-1}$, which is 75 times smaller than room temperature (RT) thermal conductivity of bulk crystalline silicon [13]. Internal interfaces and boundaries in nanostructures creates thermal carriers scattering events and tailoring the periods or structure of these boundaries offers a unique method for tuning thermal properties, while this aspect of reducing the thermal conductivity alone has resulted in ultralow thermal conductivity and proves useful for thermal barrier application.

Several other superlattice structures made of doped GaAs and differently doped a-Si:H (n–p–n–p, n–i–p–i, etc.) have also been prepared and studied [14,15]. These structures are known to exhibit interesting phenomenon like persistent photo conductivity (PPC). In PPC, current does not fall back to initial dark value after switching off the illumination, instead it shows a slow exponential decay. PPC having a life time of an order of day has been observed in doping modulated structure consisting of n–p–n–p a-Si:H based superlattice structures [16]. Such PPC effect are known to occur in c-GaAs doping superlattice structure at 4 K [17] but in doping modulated a-Si:H, PPC was not restricted to low temperature and also observed at RT or higher. It was also found that compensated a-Si:H samples having no layered structures show enhanced dark conductivity upon exposure to light at RT. The length of exposure time required is higher in case of compensated a-Si:H films compared to layered structures made of doped a-Si:H films [18]. Several mechanism have been proposed to explain the origin of PPC, for example increase in life time of carrier due to built-in-field in case of GaAs and possibly due to presence of phosphorous–boron (P–B) complex for a-Si:H based n–p–n–p structure [19,20]. It has also been reported that PPC in the doped a-Si:H multi layered structures depends on specific details of deposition conditions such as substrate temperature, degree of argon or helium dilution of silane, layer thickness and the doping concentration as well [21,22].

In this work, we report detailed study on PPC, which has been observed in a-Si:H/nc-Si:H superlattice structures, where none of the layer is doped. PPC, its dependence on exposure time, electric field, annealing temperature and the effect of increase in number of periods of superlattice structure on PPC have also been studied. A mechanism responsible for the observed PPC effect has also been proposed.

2. Experimental details

Multi layered structure consisting of 2–5 periods each of alternating a-Si:H and nc-Si:H thin films of total thickness of 700 nm, keeping the individual layer thickness equal, were deposited by Hot wire chemical vapor deposition technique. Single layer of a-Si:H and nc-Si:H together defined as one period. In both the superlattice structure, bottom layer was a-Si:H layer and the top layer was nc-Si:H. Pure silane (SiH_4) and hydrogen (H_2) were used as a precursor gases. The hydrogen dilution R is defined as $[H_2]/\{[H_2] + [SiH_4]\}$, where $[H_2]$ and $[SiH_4]$ represents the flow rate of these gases. The difference in the deposition parameters between the nc-Si:H and a-Si:H sub-layers are as follows: higher R of 85% for nc-Si:H and low R of 27% for a-Si:H, which resulted in different process pressure during deposition of two layers (Table 1). The substrate and filament temperature were kept constant at 200 °C and 1900 °C respectively and other deposition parameters are listed in Table 1. Deposition rates for a-Si:H and nc-Si:H layers were estimated by depositing single layer film under identical deposition conditions. Structural and optoelectronic properties of single and multi layered films were studied using X-ray diffraction (XRD), Raman spectroscopy, transmission electron microscopy (TEM) and electrical measurements.

XRD (Rigaku TTRAX|||18 KW) and TEM (JEOL JEM-2100) were used to examine the crystallographic orientation for single layer films. Further the samples were characterized by micro Raman spectroscopy (LabRam HR800) for structural study. Raman spectra were recorded using "Ar-ion laser" with excitation wavelength, 488 nm, in the scanning range of 300–600 cm^{-1}. The band gap of single layer a-Si:H and nc-Si:H were estimated using Tauc plot from UV–Vis–NIR transmission spectra (Shimadzu UV-3101PC) and the thickness of films were measured using surface profilometer (Veeco, Dektak 150). Electrical characterization was done using silver paste as electrodes about 1 mm apart in co-planner geometry. To ensure contact to all layers, the superlattice structures were scratched before making the electrodes. Keithley 2450 source meter was used for the electrical measurements and 100 W halogen lamp was used for illumination. Fig. 1 shows the sample structure and electrode geometry used in this work.

3. Results and discussion

Fig. 2 show the XRD pattern of the single layer a-Si:H and nc-Si:H thin films recorded using Cu Kα radiation (λ = 1.54 Å) with scanning range from 15° to 70°. XRD studies suggest that the films prepared at low R are amorphous in nature with

Table 1
Deposition parameters and band gap of single layer of a-Si:H and nc-Si:H thin films.

Type	No. of layers	Process Pressure (mbar)	SFR (sccm)	HFR (sccm)	Bandgap (eV)
nc-Si:H	Single	0.2	2.7	15	2.1
a-Si:H	Single	0.02	2.7	1	1.9