Chapter - 7
Conclusions

7.1 Summary

The aim of this thesis is the development of silicon nano-crystals (Si-ncs) and quantum dots (Si-QDs) dispersed within a dielectric matrix of a-SiC or a-SiO\textsubscript{x} and in the superlattice structures with alternative layers of nc-Si:H and a-Si:H, precisely in low temperature plasma CVD and rf-magnetron sputtering units at a comparatively low-temperature (< 400°C), compatible for different layer fabrication of all silicon solar cells at low cost.

The work begins with the development of superior absorber layer for nanocrystalline silicon solar cells in which the optical and electrical properties have been tuned by controlling the size of the silicon nanocrystallites as the consequences of quantum confinement effect. The silicon nano-crystallites has been fabricated in a nc-Si:H/a-Si:H superlattice structure wherein the size of the Si-nc is being regulated by means of changing the thickness of each nc-Si:H sub-layer. On gradual thinning of nc-Si:H sub-layer within 8–3 nm, significant enhancement in optical absorption at near-UV photon energies along with simultaneous optical band-gap widening within 1.89–2.04 eV has been observed owing to the quantum size-effect on Si-ncs. The vertical electrical transport phenomena accomplished in superlattice films have followed the prevailing Poole-Frenkel tunneling which enables effective utilization of the nc-Si:H/a-Si:H superlattice films in practical device configuration.

In order to accomplish appropriate absorber and window layer films in the top sub-cell for all-Si tandem structured solar cells, intrinsic and doped thin films of nanocrystalline silicon quantum dots embedded in amorphous silicon carbide (nc-Si–QD/a-SiC) having wide optical band gap and superior electrical conductivity, have been prepared at low plasma pressure of inductively coupled plasma CVD at low substrate temperature. At first, the intrinsic nc-Si–QD/a-SiC thin films have been prepared in (SiH\textsubscript{4} + CH\textsubscript{4})-plasma with hydrogen dilution showing improved electrical conductivity at wide optical band gap due to the presence of tiny silicon nano-crystallites. However, a high hydrogen dilution consequence a low growth rate that severely retards the cost-effective
production of nc-Si QD-based devices. Keeping that in consideration, the next phase of the research work deals with the synthesis of nanocrystalline Si quantum dots embedded in an amorphous SiC matrix (nc-Si–QD/a-SiC) from the gas mixture of silane and methane without any additional hydrogen dilution where the intrinsic nc-Si–QD/a-SiC films demonstrate high growth rate, a significantly high electrical conductivity at wide optical band gap, which could be used as the efficient intrinsic absorber layer for the nc-Si solar cells. Finally, nanocrystalline Si quantum dots embedded in amorphous SiC matrix (nc-Si–QD/a-SiC) doped with phosphorous have been synthesized which has been found to have significantly high electrical conductivity (~$10^{-1}$–$10^{-2}$ S-cm$^{-1}$) with wide optical gap (>1.90 eV) which would have favorable application as the $n$-type window layer in $n$-i-$p$ nc-Si solar cells in superstrate configuration.

In realizing energy selective contacts for hot carrier solar cells, which can absorb higher energy photons, thin films of Si-QD/a-SiO$_x$ having double barrier structure has been achieved at a low temperature ~400°C, from one step process by reactive rf magnetron co-sputtering of c-Si wafer and pure SiO$_2$ targets, in the ($H_2$+Ar)-plasma. Formation of a double-barrier structure has exhibited the elevated current density in some definite range in current density vs. electric filed plots exhibiting NDR-like effect arising due to the discrete energy levels of c-Si QDs, which is quite interesting in view of its appropriate application as the energy selective contacts in hot carrier solar cells. However, the wide peak-width due to the larger size-distribution of c-Si–QDs suggests insufficient energy selectivity. Further work is focused on improving the quality of the material and position and quality of the resonance peak.

### 7.2 Future Outlook

As some very exciting new material and several new physics related to that material were explored in the course of this project, there is a lot of scope to utilize the material in various device fabrication. During the present course of work, the Si-QDs have been obtained. However, to successfully integrate in nano-electronics devices silicon quantum dots (Si-QDs) density, density uniformity, size and size dispersion must be controlled with a great precision to limit electron tunneling between adjacent crystallites. A similar requirement appears essential in obtaining better performance in all-Si QDs based tandem
solar cells where the individual band gap of each active layer of different stacking solar cells needs to be accurately controlled by the specific size and distribution of Si-QDs. Although, we are successful to synthesize the QDs of very high density and small size dispersion, we have to focus on further optimization of the plasma parameters to get a high density and as well as uniformly distributed quantum dots for all size dots.

In achieving high efficiency solar cells at low production cost (i.e. third generation solar cells) there are two significant avenues – one such is the multi-junction solar cell and another one is hot carrier solar cells which can boost the efficiency progressively by utilization of the extended solar spectrum. In multi-junction solar cells, different absorber materials can be used in stacked layer configuration and the optical and electrical properties of the each layer, whether it is doped or intrinsic, should be tuned in such way that light can be efficiently absorbed in each absorber layers and the photo-electron produced can also be proficiently collected in the doped layers. During this project, such tuning of the properties have been successfully achieved which can be utilized in the practical application of the photovoltaic devices. Using the CVD process, the next study would surely involve in the critical utilization of superlattice thin films and window layer materials in the top cell of multi-junction solar cells. The accomplishment of the all silicon multi-junction solar cells also requires development of other materials for the bottom and middle cells by proper plasma processing. So, this could be one topic that can be explored in near future.

For hot carrier solar cells, the energy selective contacts have been successfully developed which exhibits peaked current density at some definite applied electric field at which hot electrons can be collected. However, the broad peak in the current-voltage characteristic prohibits the present developed material for its immediate practical utilization. There should be much effort in narrowing the peak of the current-voltage characteristics by fine tuning of the size and size-distribution of the crystalline silicon quantum dots. In addition, hot carrier solar cells requires an absorber layer which would not slow down the highly energetic photo-electrons by means of elastic collision at the lattice points in the absorber material. Considering that, the superlattice thin film developed here could be promising one and that could be another matter of interest which can be investigated in near future.
Photoluminescence is one of the important properties of this nanostructure that could be explored. Silicon-based light-emitting diodes (LEDs) represent promising candidates for the next generation of full-color flat panel displays, optical interconnections, telecommunications, and lasers. The advantages of silicon-based LEDs include complementary metal-oxide-semiconductor compatibility, system feasibility, and their low cost of fabrication. So, the material with quantum confinement effect can also be applied for LEDs.

7.3 Conclusions

In conclusion, the present research project deals with the development of silicon nano-crystals (Si-ncs) and quantum dots (Si-QDs) embedded within a dielectric matrix (a-SiC and a-SiOₓ) and the nc-Si/a-Si:H superlattice structures, specifically through low temperature CVD processing and rf-magnetron sputtering at a comparatively low-temperature (< 400°C), compatible for fabrication of different layers of the all silicon solar cells with third generation technology at low cost. Comprehensive investigations of these nano-structured thin films on their structural, optical and electrical properties have been studied in view of their optimization and application in the assembly of devices. It is our hope that the present work, which has explored a new process of formation of silicon nano-crystals and quantum dots embedded in dielectric matrix and superlattice structure and its high quality in optical and electrical properties could open up a convenient avenue for the fabrication of devices such as, e.g., all-silicon third generation solar cells, photodetectors, light-emitting diodes, single electron transistors and the Q-bit operations in the quantum computations etc.