# CHAPTER 6

# CONCLUSIONS AND FUTURE WORKS

## 6.1 CONCLUSIONS

In this work, good quality, high density and well-aligned SiNWs have been synthesized at low deposition temperature using a home-built dual mode plasma-assisted hot-wire chemical vapour deposition system. This system has the advantages of being a simple low-cost system which is capable of depositing the catalyst and growing the SiNWs all within the same reactor, thus reducing the possibility of contamination of the SiNWs due to exposure to external environment.

### *6.1.1 From Au catalyst to In catalyst*

Under the deposition conditions studied in this work, Au islands are only able to induce the growth of short SiNWs, while In/Au islands resulted in the growth of longer SiNWs. Further investigation shows that In can act as effective catalyst for the growth of NWs without assistance of Au element. Large catalyst droplet capping on top of the SiNWs is one of the common characteristics of the In-catalyzed SiNWs. However, the large In islands induce the growth of non-aligned SiNWs, which are worm-like in structure. The result shows that the alignment of the NWs can be improved by reducing the size of the In catalyst islands to 137 nm or less. The size of the In caps on the aligned SiNWs is reduced through evaporation in conjunction with the axial upward growth of the NWs. The results from this work show that the axial growth process is terminated when the size of the In caps reaches the limit for inducing the growth, resulting in the formation of the tapered NWs with sharp tips. Due to the low Si solubility of In, the successful growth of the SiNWs from In catalyst islands is highly dependent on the amount of silane radicals fed into the In catalyst islands. Higher rf power in PECVD and higher filament temperature in HWCVD enhance the number of $SiH_x$ radicals reaching the catalyst, thus increasing the possibility of growth and density of the SiNWs.

### *6.1.2 From PECVD to HWCVD*

The use of PECVD to discharge the $SiH_4$ precursor diluted in $H_2$ has successfully induced the growth of SiNWs at substrate temperature below 400$^o$C. The highest NWs density of ~0.9 $\mu m^{-2}$ was obtained at rf power of 80 W (power density of 1018 $mWcm^{-2}$). However, the growth of the SiNWs is totally suppressed by further increasing the rf power to 100 W (power density of 1273 $mWcm^{-2}$). Although higher rf power density (below the rf power limit) can induce the successful growth of SiNWs from the catalyst islands, it also increases the ion bombardment effects on the NWs. The undesired ion bombardments destroy the crystallinity of the SiNWs, resulting in the formation of SiNWs with Si nanocrystallites embedded amorphous phase at higher rf power. The results showed that in order to synthesize SiNWs with high crystallinity, the limit of rf power applied must be less than 40 W (power density of 509 $mWcm^{-2}$). From further investigation, HWCVD proved to be an effective technique for synthesis of SiNWs via In catalyst due to the high rate of $SiH_4$ gas dissociation. HWCVD is free from ion bombardment effect. Thus it was shown to be able to produce high crystallinity of SiNWs due to the increase in the number of reactive atomic H reaching the growth sites and enhancing its etching effect. In HWCVD, filament temperature serves as an important parameter for controlling the decomposition of the silane precursor gas. The successful growth of In-catalyzed SiNWs is observed at filament temperature of 1500$^o$C and above. However, the NWs grown at filament temperatures of 1500 and 1600$^o$C are mostly kinked in structure. Increase in filament temperature to 1700$^o$C and above is shown to grow straight and well-aligned SiNWs with aspect ratio up to 20.

### *6.1.3 Formation of In-catalyzed Si nanowires using HWCVD*

From the study on the growth process of the In-catalyzed SiNWs, it is shown that the structures of the SiNWs can be engineered through understanding the axial and radial growth mechanisms and the catalyst kinetic during the growth. The catalytic growth of SiNWs from the In catalyst islands form single crystalline structures. The uncatalyzed silane radicals surrounding the NWs form slanting nanocolumnar Si structures on the walls of the NWs. The growth of NWs is terminated due to the complete migration of In catalyst, whereby the growth process is then continued with radial growth of the slanting nanocolumnar Si structures. This results in the formation of c-Si/slanting Si nanocolumns core-shell NWs.

## 6.2 RECOMMENDATIONS FOR FUTURE WORKS – TOWARDS APPLICATIONS

The growth and structural properties of the In-catalyzed SiNWs were studied in this work. The optical properties such as optical reflection and photoluminescence of the as-grown SiNWs samples were examined but not included in this thesis. Future works recommended should be focused on the potential applications of these SiNWs based on their morphology and structural properties.

### *6.2.1 Field emitters*

The tapering SiNWs with sharp tips can be utilized as field emitters for vacuum nanoelectronics, flat panel field emission displays and spacecraft applications. Field emission is a phenomenon where the electrons within the semiconducting materials tunnel through the surface potential barrier to vacuum by applying high electric field. The low work function of Si (~4) makes these NWs one of the suitable materials for field emitter. In order to obtain good field emission properties, the SiNWs should be engineered to have high aspect ratio and small tip geometry in order to lower the turn on field and current density for electrons emission. Another important parameter to consider is the distance between neighbouring SiNWs. This distance should be almost equal to the height of the NWs in order to minimize the screening effect produced by the neighboring NWs. A rough study carried out on the as-grown SiNWs using a home-built field emission system showed promising field emission produced by the tapering SiNWs (refer to Appendix A).

### *6.2.2 NWs based solar cell*

SiNWs based solar cells have attracted considerable attention due to the increased improvement in photon absorption efficiency compared to the conventional planar Si solar cells. In particular, two important aspects have to be considered, namely the photon absorption ability and the electrical charge transportation of NW arrays, in order to improve the energy conversion efficiency in the NWs solar cells. The high electrical conductivity due to the single crystalline structures of the SiNWs promises an efficient transportation for charge carriers. The high absorption property of the SiNWs can be achieved due to the high densities of the SiNW arrays, which can act as traps for photon through the total internal reflection within the NWs. The presence of the radial growth structures on the sidewalls of NWs is expected to further improve the light absorption ability by increasing the surface area to volume ratio, hence, improving the photon absorption of the SiNWs over a wider range of wavelengths. This structures can be modified to suit the NWs based solar cells and photovoltaic applications.

### *6.2.3 Thermoelectric devices*

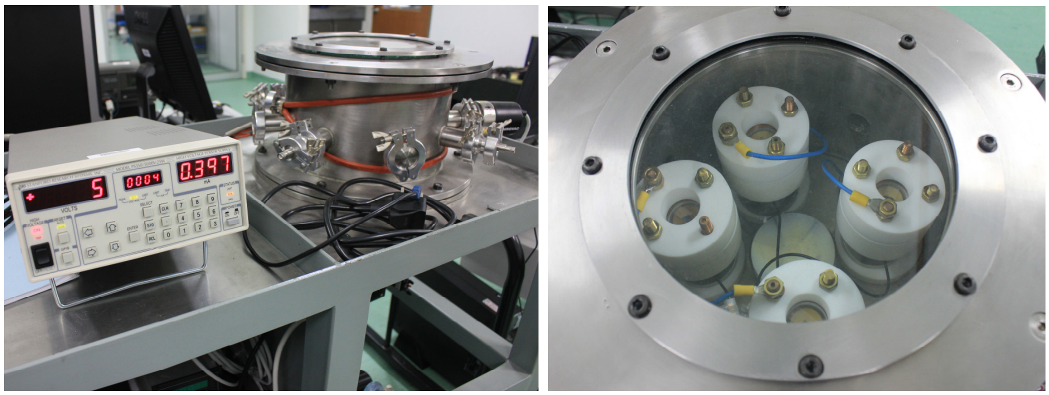
The one step growth of the self-assembled c-Si/slanting nanocolumns nc-Si core-shell NWs could be used as elementary building blocks in future nanoelectronic and thermoelectric devices. The single crystalline Si core can serve as a high electrical conducting medium to conduct electricity. The high surface roughness due to the nanocolumnar nc-Si shell could slow down the phonon transport and minimize the heat loss to the surroundings. The results show that the slanting angle and crystallinity of the Si nanocolumns shell can be engineered by controlling the deposition parameters for this application.

The potential applications of the In-catalyzed SiNWs should not be limited to the above mentioned areas. However, it still needs a lot of tough, creative and systematic works to implement them for industrial applications to benefit mankind in the future.

# APPENDIX A:

# FIELD EMISSION PROPERTIES OF SILICON NANOWIRES

(a) Field emission system setup



(b) Field emission measurement on In-catalyzed SiNWs