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Reaction between Energy Particle Ion Beam with Carbon Nanotube

Qintao Li, Zhichun Ni and Shehla Honey

Abstract

Carbon nanotubes (CNTs) have attracted considerable attention due to their high aspect ratio, whisker-like form for best possible geometrical field enhancement, high electrical conductivity, and extraordinary thermal stability. Ion beam technology is a potential technique for controlled construction of CNTs. During collision with energetic ions, carbon atom of CNTs can get an adequate amount of energy to escape from the graphite lattice and produce a large number of defects. These defects are advantageous for adding some new functional groups and nanoparticles to modify CNTs. Meanwhile, the structure and atoms in the region of the defects can be rearranged and changed into amorphous structure, onion structure, and so on. These defects also can be used to form the junctions of CNTs and realize welding of CNTs and network formation of amorphous carbon nanowires.

Keywords: carbon nanotubes, ion beam, modification, welding, structural change

1. Introduction

Ion beam technology has some advantages for controlled construction and modification of nanostructures; i.e., (1) nonequilibrium phase transition of nanostructures can also be realized using ion beam technology, and the nucleation in phase transition process will not be confined due to thermodynamics of growth of material. (2) The lattice orientation of nanostructures can be controlled using a channeling effect of ion beam. In fact, when a beam of energetic ions interacts with crystal, it can destroy the nanoparticles while keeping maintained the crystal nuclei and nanoparticles with orientation consistent with channel direction of ion beam. (3) Ion implantation is an effective means for nucleation, nanophase formation, nanocrystal orientation, and precise doping. (4) Ion beam deposition technology is also an effective way to achieve high-quality thin films.

In the past three decades, ion beam technology has played an important role in the formation of nanostructures, such as alloying, amorphization, and phase transformation; nanocrystalline phase formation by ion implantation; nucleation induced by ion implantation; oriented nanocrystals in solid-state network; and nanocrystal size control [1–4].

CNTs can be employed as conducting wires and building blocks of many electronic and optoelectronic nanodevices due to their excellent mechanical and electronic properties [5–8].

In recent years, some important research topics in the interaction between the ion beams and CNTs have attracted widespread attention. The energy, doses, and the substrate temperature of ion beams should affect the interaction results.

In general, if the energy is very low (such as 100 eV), the cascade collision effect does not occur. The interaction between ion beam and CNTs is producing the defect in the graphite lattice, and the structure of CNTs is still graphite shell. In this range of ion beam energy, the number of defect on the CNT surface can be controlled precisely by adjusting the ion energy and ion doses, and the corresponding properties of CNTs can be tuned. These defects can be used as the source to add some new functional group, functional material, and nanoparticles. Even, the C atoms around the defects can be transferred into the carbon onion structure or diamond by the H ion beam. When the energy is high (such as 30 keV), the cascade collision effect occurs, and it can produce a large number of defects by the implantation of ion beam. In this ion beam energy range, the graphite layer structure of CNTs should be damaged under the irradiation of ion beam. The rearrangement of carbon atoms should happen. The amorphous carbon nanostructure, carbon onion structure, or diamond structure can be formed. The defects can also be used to link the CNTs, and the welding of CNTs can be realized. Therefore, the modification of CNTs, transformation of CNTs, welding of CNTs, fabrication of carbon nanowire networks, etc. have been interesting under the interaction between the ion beam and CNTs.

2. The interaction between CNTs and ion beams

2.1 The modification of CNTs by ion beams

When the energy of ions is very low, the penetration depth of ion beam is only several nanometers, and the damage produced by ion beam occurs on the surface of CNTs. The achieved energy of carbon atom in the CNTs by the collision is small. Therefore, the interaction between ion beam and the CNTs in this energy range should produce the lattice defects. These defects can be used to adjust the mechanical, electronic, and optoelectronic properties. The defects can also be used as the sources to add some new functional group, functional structure, and nanoparticles. The CNTs can be modified by non-covalently attached or covalently attached means through some chemical technology, chemical vapor deposition (CVD), etc. [9–12]. The structure by the noncovalently modification is unsteady. The hybrid material by the covalently attached means has a very strong force between the CNTs and the functional group, function structure, or nanoparticles. In general, the CNTs can be modified by covalently attached means under the irradiation of ion beams. The connection between CNTs and the functional group, function structure, or nanoparticles depends on the formation of the new covalent bond around the defects induced by the ion beams. The hybrid material is very steady. The modification of CNTs should be some new complex properties by the introduction of some new structure and can be used as new composite material.

In our previous work [13, 14], the interaction between CNTs and hydrocarbon ion beams having energy in the range 80–200 eV with substrate temperature from room temperature to 700°C has been studied. The ion beams are produced by Kaufman ion source. The CNTs are dispersed on the silicon wafer as the sample. **Figure 1** represents SEM images of CNTs being irradiated by hydrocarbon ions with 80 eV and different percentages of hydrogen in gas phase.

After CNTs are being irradiated by hydrocarbon ions, surface of CNTs becomes rough, and diameter is increased. As the ratio of $H_2:CH_4$ will be increased in gas phase, diameters of CNTs will decrease such as 60–70, 40–50, 8–40 nm to forming fragments and clusters. In the process hydrocarbon ion irradiation, there are two competing effects.

The first effect is deposition of carbon and carbon-based ions, and the second is etching of hydrogen ions.

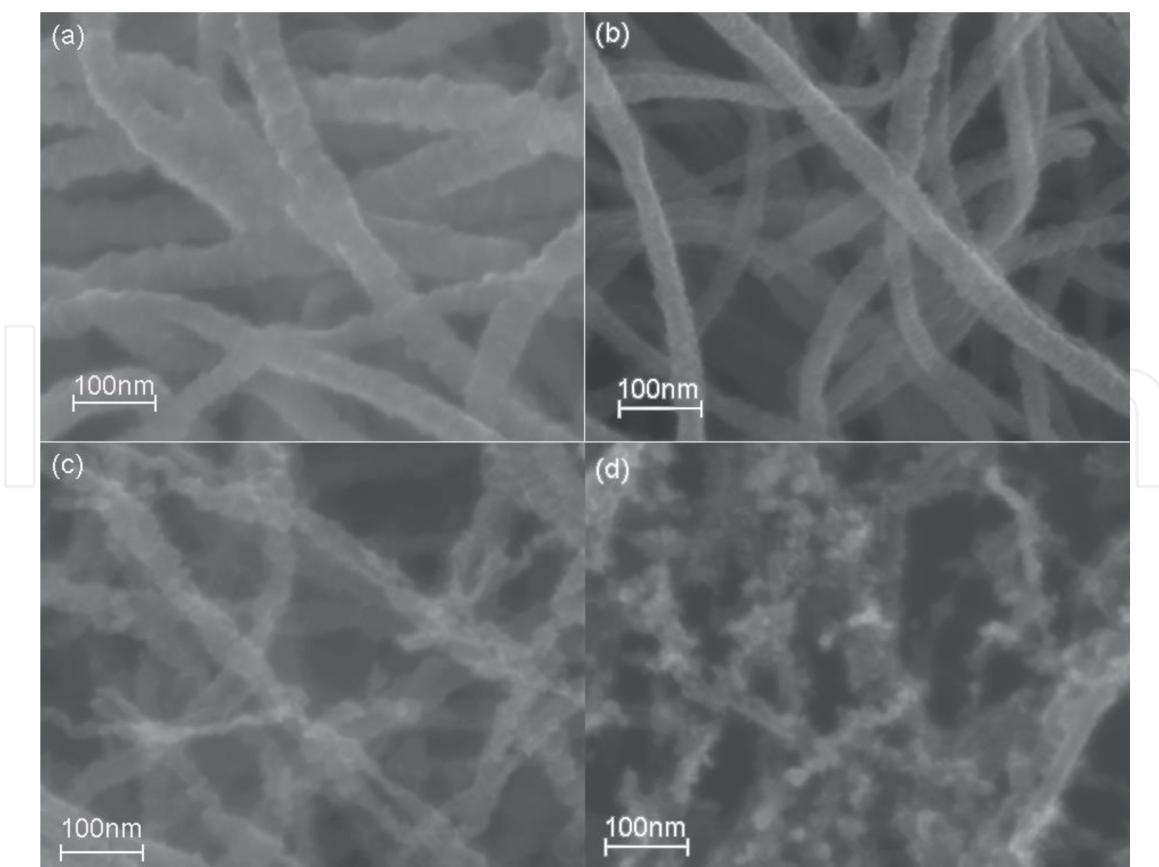


Figure 1.
 SEM images of CNTs being irradiated by hydrocarbon ions of energy 80 eV and varying ratios of $H_2:CH_4$, i.e., (a) 0; (b) 10:1; (c) 20:1; and (d) 30:1 [13].

The deposition rate is high due to dominance of deposition effect in case if hydrogen content is less in gas phase. If the hydrogen content is intermediate in the gas phase, then deposition rate will be time-consuming which results in depositing a thin layer. At high content of hydrogen ions, the deposition rate of carbon-based ions is entirely suppressed due to dominance of etching effect. The bare exposure of CNTs to hydrogen ions initiated the etching of CNTs which leads to etch these CNTs in parts and finally results in formation of pieces of carbon clusters. **Figure 2** represents TEM images of CNTs being exposed to 80 eV hydrocarbon ions ($T = 700^\circ C$).

The surface of CNTs is rough and inner hollow structure is undamaged. The selected area electron diffraction pattern (SAED) displays reflections (002 and 004) which correspond to intergraphene. **Figure 2b, c** represents the high-resolution transmission electron microscope (HRTEM) images of CNTs after treating with hydrocarbon ions having ratio $H_2:CH_4 = 5:1$ at $700^\circ C$ for 30 and 90 min, respectively. Carbon nanoparticles of graphene stacks in size of ~ 5 nm are formed on the surface of CNTs after the treatment of 30 min, and the whole surface is covered with a coating of graphene stack carbon nanoparticles (size ~ 15 – 20 nm). HRTEM image of CNTs after being treated with hydrocarbon ions having ratio $H_2:CH_4 = 10:1$ for 90 min at $700^\circ C$ is shown in **Figure 2d**.

The whole surface of CNT is covered with a coating of carbon nanoparticles of graphene stacks (size ~ 5 nm) and highlighted in the region encircled as “D.” The existence of a large number of defects can obviously be seen in the regions that are encircled as “E” and “F.”

High temperature is believed to be the most important factor in order to form the carbon nanoparticles of graphene stacks. Usually, carbon nanomaterials that grow on low temperature have amorphous structures. Besides, at high temperature carbon clusters are oriented in the film due to SP^2 carbon because of a sharp drop

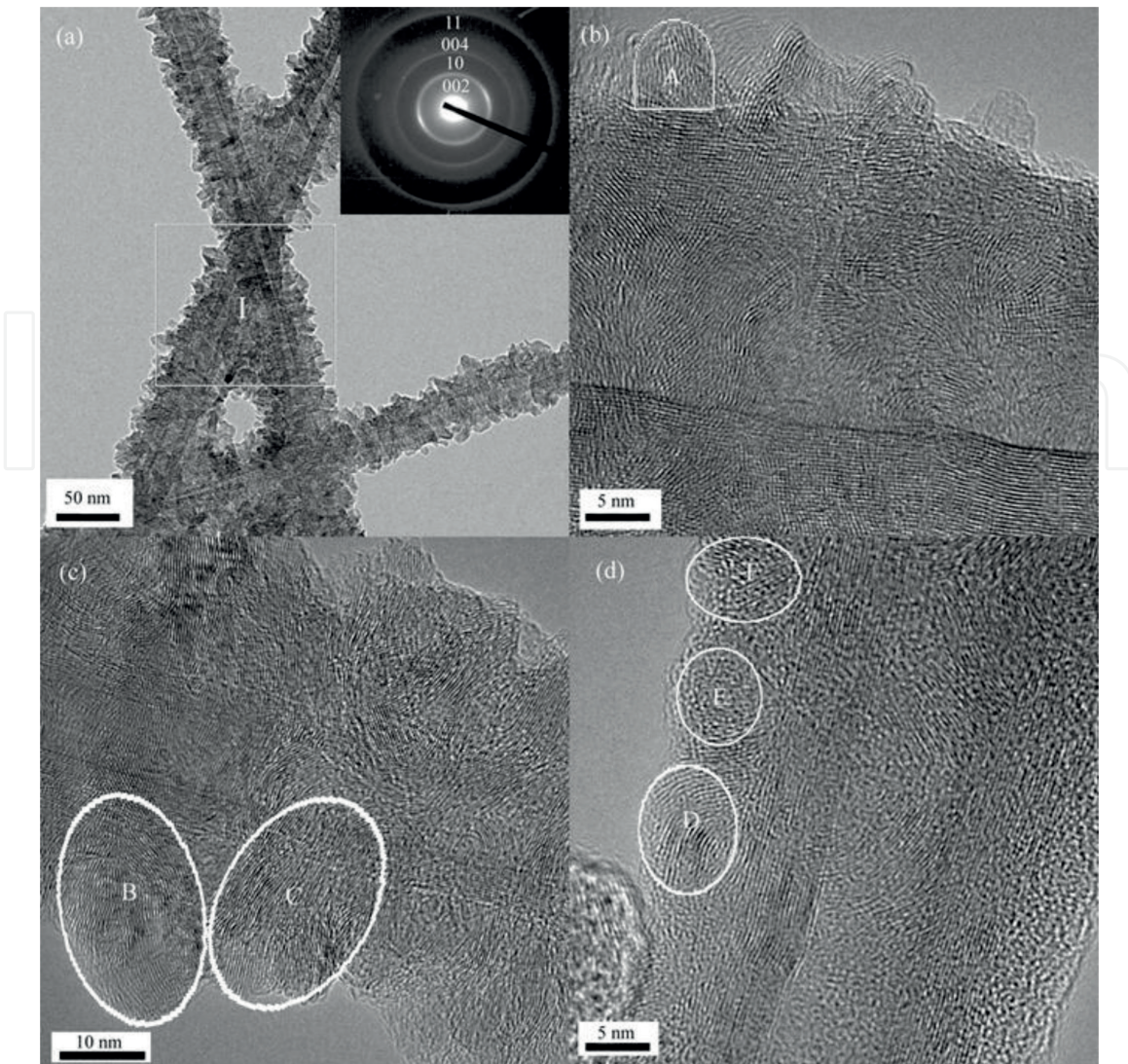


Figure 2.
TEM images of CNTs being irradiated by hydrocarbon ions [13].

in SP^3 fraction of carbon with increasing substrate temperature. Usually, all carbon materials that grow at low temperature have a common characteristic of amorphous structure. Turbostratic stacked graphenes are formed due to structural modifications which occurred at high annealing temperature.

Structural defects such as vacancies and interstitials may be generated due to collision cascade effect on walls of tubes due to the bombardment of hydrocarbon ions. The dominant defects are single vacancies. Thereafter, a pentagon ring is formed by these single vacancies which are escorted by movement of dangling bond atoms away from the shell by the distance 0.5–0.7 Å. Saturation in defects by hydrocarbon bonds will occur due to the effect of active hydrogen ions. Subsequently, protruding atoms induce a stress in the crystal lattice which will put neighboring bonds at risk of additional hydrogenation. In the meantime, active hydrocarbon atoms replace hydrogen atoms by process of abstraction and adsorption of hydrogen and lead to deposit the carbon. The deposited carbon will make carbon nanoparticles of graphene stacks extended from the surface under the influence of high-temperature annealing.

Penetration depth for 80 eV hydrocarbon ion CNTs is ~1 nm; therefore, ion irradiation induces the damage in the topmost shell, and graphene will be formed up to a depth of few “nanometers” which will protect CNTs from further damage.

Initially, the distribution of nanoparticles over the surface of CNTs is random. Later, the surface of CNTs will be entirely covered by a coating of carbon

nanoparticles of turbostratic stacked graphenes with increase in deposition time. As the hydrogen content in gas phase will be increased, the deposition effect is subdued, and carbon atoms of C–H bonds are supposed to be etched by hydrogen ions prior to assembly with active hydrocarbon ions which lead to appear as the amorphous carbon.

Hence, structural quality and size of carbon nanoparticles of turbostratic stacked graphenes are lessened.

When the CNTs are dispersed on Cu network as the sample and substrate temperature is about 900°C, a new complex material of CNTs decorated by graphitic shell-encapsulated Cu nanoparticles is achieved [15]. After treating with hydrocarbon ions, internal vacant CNT structure remains safe, whereas surface becomes extremely rough.

HRTEM image of **Figure 3** shows the products that are composed of Cu-C core-shell structure nanoparticles with core size 1–2 nm (size of shell = 5–10 nm). The core nanoparticles are firmly encased in carbon shells without having any space in between shell and core. The shells are composed of 8–10 layers and have equal thicknesses.

When the hold substrate of CNTs is copper, the substrate is heated to 900°C. Comparing with the hold substrate of silicon, some new process is produced: initially, several Cu atoms can gain adequate energy and fled from surface of substrate at elevated temperature and turned into Cu species. Thereafter, carbon and Cu alloys were formed due to the interaction of Cu and carbon species introduced by means of low-energy hydrocarbon ions. Afterward, with the period of hydrocarbon ions, dissolution of carbon in Cu nanoparticles approaches saturation, and a precipitation of pure carbon around the nanoparticles would commence in shape of graphite; consequently, the graphitic shell-encapsulated Cu nanoparticles are formed.

To sum up, only defects can be created on the surface of the CNTs, and the cascade collision effect does not happen during the irradiation of low-energy ion beam. The new functional groups or new nanostructures are connected on the carbon atoms by covalent bond through utilizing the activity of the defects and form new complexes. The CNTs after modification have some new properties. These new composite materials can be used as new chemical materials, electrical materials, mechanical materials, etc. and can be applied in the fields of medicine, functional chemistry, catalysis, field emission, composite mechanical materials, etc.

2.2 The phase transformation occurred by ion beam irradiation

When the energy of ions is high, the carbon atom can gain enough energy to escape from the graphite lattice of CNTs in the collision process and can be a free atom. The free carbon atoms should collide with the other carbon atoms in the

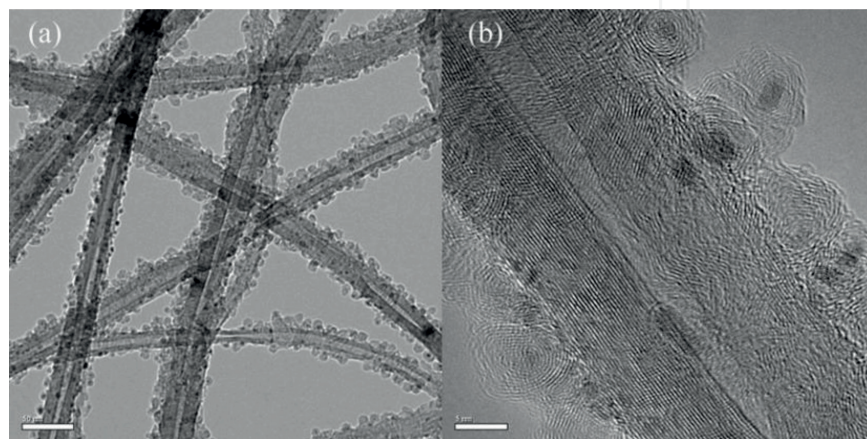


Figure 3.
The TEM image of CNTs decorated by graphitic shell-encapsulated Cu nanoparticles [15].

lattice to decrease its energy and stop inside the CNTs until its energy is zero. The cascade collision effect happens, and a large number of lattice defects should be produced. In the cascade collision process, the order of the crystal lattice will be destroyed, and even the hollow tube structure may be destroyed [16]. The CNTs can transform into the other structure, such as amorphous structure. In the disappearance process of the tube structure, the carbon nanowire with some special morphology structure may be formed such as case, pillbox-like, etc. If the substrate temperature is high, the disordered carbon atom should be rearranged and can transform into the carbon onions or diamond-like carbon structure or even diamond structure. Structural evolution of CNTs irradiated by in situ electron beam carried out by Banhart et al. designated that basal planes of CNTs were found to be cracked, crooked, and tilted after irradiation [17, 18]. In another report, structure of CNTs had been modified to carbon onion or diamonds [19]. Wei et al. irradiated CNTs by beam of 30 or 50 keV Ga ions at a range of fluencies [20]. In their report, at the low beam fluence $\sim 10^{13}$ ions/cm², they found alteration of CNTs from well-ordered pillbox-like nano-compartments of unfixed lengths to amorphous rods without changing the tubelike shapes of CNTs. At high beam fluence $\sim 10^{15}$ ions/cm², CNTs were modified in form of homogenous amorphous rods.

Kim et al. found alterations in morphologies of CNTs after exposure to beams of 4 MeV Cl ions [21]. In their report, morphologies of CNTs had been altered from CNTs to nano-compartments having bamboo-like structures inside the tubes at a fluence $\sim 3 \times 10^{16}$ ions/cm². They reported the reason for formation of nano-compartments with bamboo-like structure by folding the inner walls.

In our previous work [22], the interaction of CNTs and a 40 keV beam of Si ions at fluencies $\sim 1 \times 10^{15}$ and $\sim 1 \times 10^{17}$ ions/cm² in a 100 keV electromagnetic isotope separator is investigated. HRTEM representations of CNTs exposed to a beam of Si ions having fluencies ranging from 5×10^{15} to 1×10^{17} ions/cm² are shown in **Figure 4**.

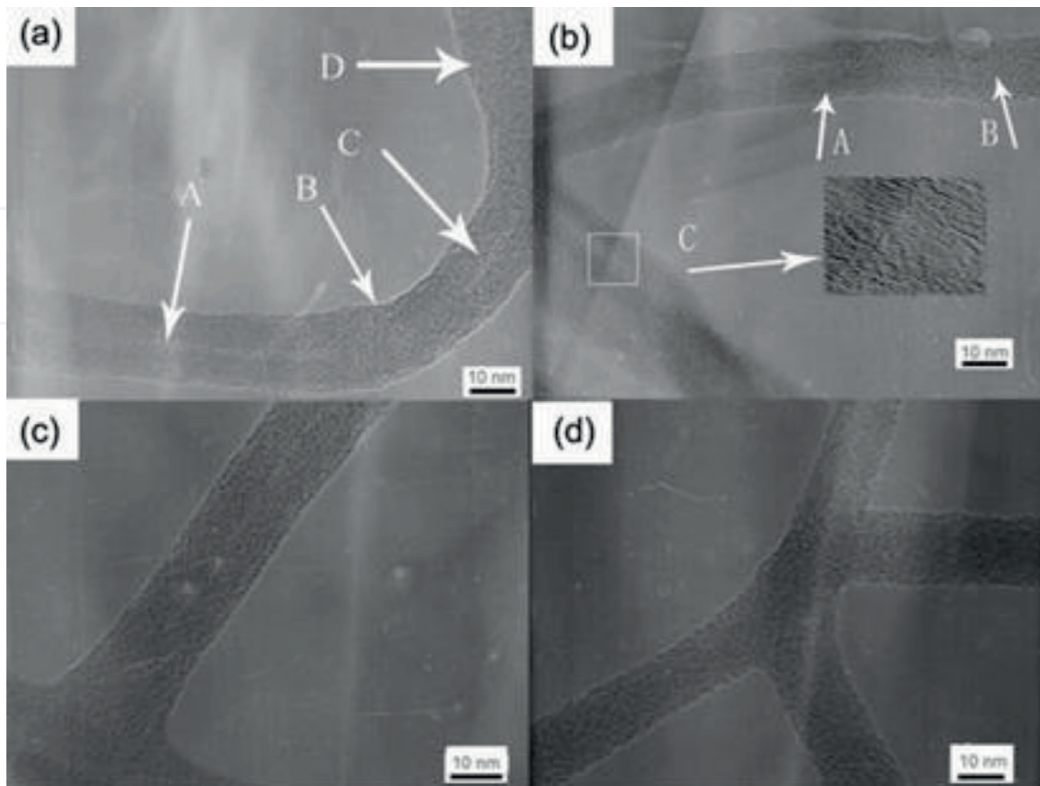


Figure 4.
TEM images of CNTs by irradiation of 40 keV Si ion beam at fluence of 1×10^{15} – 1×10^{17} ions/cm² [22].

With beam fluencies of ions ranging from $\sim 5 \times 10^{15}$ to $\sim 1 \times 10^{17}$ ions/cm², CNTs transformed into CNTs with some disorder in graphite structures and integral hollow tubular shape, semisolid carbon nanowire having amorphous structure and unfilled tubular shape, semisolid amorphous carbon nanowire with intermittent unfilled case to solid structure amorphous carbon nanowire.

The procedure for structural modifications of CNTs and fabrication of amorphous carbon nanowires is shown in the model diagram of **Figure 5**. During the ion beam bombardment of CNTs by Si ions, an energetic ion transfers its energy to the atoms of the topmost shell, and several recoils of primary carbon atom and vacancies will be formed in this way. These recoil atoms will produce more recoils by colliding with carbon atoms in other shells of CNTs. Structure of nanotubes becomes highly unstable due to the presence of large number of defects, i.e., vacancies and interstitials, and carbon atoms in graphitic structures around vacancies will reorganize to lessen the surface free energy.

Consequently, well-ordered graphite sheets of CNTs are divided into local ordered graphite. Production of defects is gradually increased with increasing beam fluence. The tube walls of CNTs with local ordered graphite will then be transformed into completely disordered phase having hollow structure due to continuous production and collection of defects.

Amorphous carbon nanowires are formed in the first period. Secondly, at higher irradiation doses, the semisolid amorphous carbon nanowires converted entirely into solid amorphous carbon nanowire. The nanotubes alter into multishelled pillbox-like nanocompartments prior to breakup in form of homogenous amorphous rods in later case. The procedure for makeup of solid amorphous carbon nanowire at an intermedial stage is displayed in the structure. In addition, CNTs used in this experiment were dispersed randomly on substrate and overlapped.

Low beam fluence is received by a shielded part of the tube in comparison with unshielded part as beam of energetic ions assails tubes. Consequently, disordered graphite, semisolid structure, and solid structure are found concurrently on nanotubes irradiated by the almost the same beam fluence.

In our previous work [23], the interaction of CNTs and 1.2 keV Ar ion has been investigated. **Figure 6** shows the SEM images of CNTs irradiated by 1.2 keV Ar ions for 15–60 min. After 15 min sputtering, the tube shapes of CNTs are almost intact, and the diameters of CNTs are 4–35 nm, and only a few CNTs are broken into several parts along the tube axis; the inset TEM images of typical CNTs shows that the CNTs are transformed into amorphous carbon nanowires, consistent with the results of 40 keV Si ion irradiation. After 30 min irradiation, the CNTs are separated into some particles with the size from 20–30 to 300–400 nm along the tube axis, and the surfaces of particles are smooth with no conical protrusion.

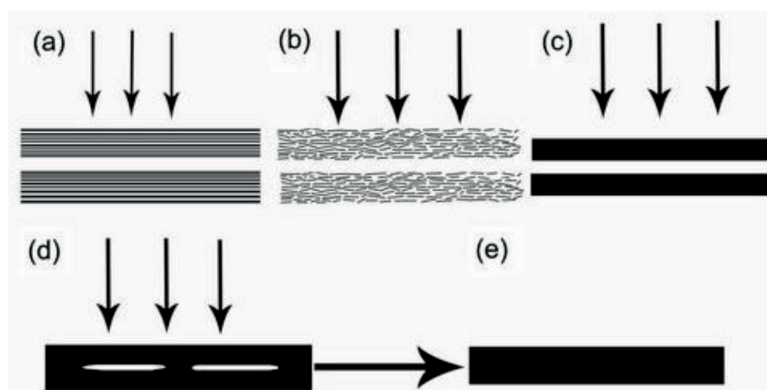


Figure 5.
 The process of amorphous carbon nanowire formation by 40 keV Si ion beam irradiation [22].

After 45 min sputtering, the all-tube morphology of CNTs on the top layer of CNTs stacks is broken, and the tube morphology of CNTs at the bottom of CNTs stacks is almost intact; some protrusions can be observed on the coarse aggregated nanoparticle surface. With 60-min sputtering, all CNTs are broken, and some nanofibers can be observed; the lengths of nanofibers are ranged from several ten nanometers to several micrometers. The high-resolution SEM images of typical nanofiber show that the nanofibers grow on the tip of protrusion. The formation of carbon nanofibers by Ar^+ sputtering CNTs is speculated.

Initially, structures of CNTs are modified due to the presence of large number of defects, i.e., vacancies and interstitials between and on tube walls due to collision cascade effect that gives rise to degree of disorder in the structure, and consequently, CNTs might be scrunched up in form of amorphous nanowires.

Carbon atoms are sputtered quickly on some regions because of difference in sputtering yields which depends on curvature of the amorphous nanowire surface and lead to break CNTs, and some particles will be deposited along the axis of tubes. Afterward, flanges are formed due to competition between smoothing process and roughening process. At last, the migration of mass redeposition atom toward the tip leads to the growth of carbon nanofibers on the protrusion.

2.3 The welding and the carbon nanowire network fabrication

The fabrication of components on nanoscale is required for the construction of modern electronic and optical electronic nanodevices. The nanoscale interconnections are also required between building blocks and in interior of building blocks in order to obtain further miniaturized nanoscale devices. CNTs or metallic or semiconductor nanowire can be used as interconnection in electronic devices. Until now, various nanometer-scale optical electronic and electronic devices have been constructed successfully via uncomplicated interconnections, but still a lot of difficulties are arising in constructing complicated devices. Major technical obstacle is

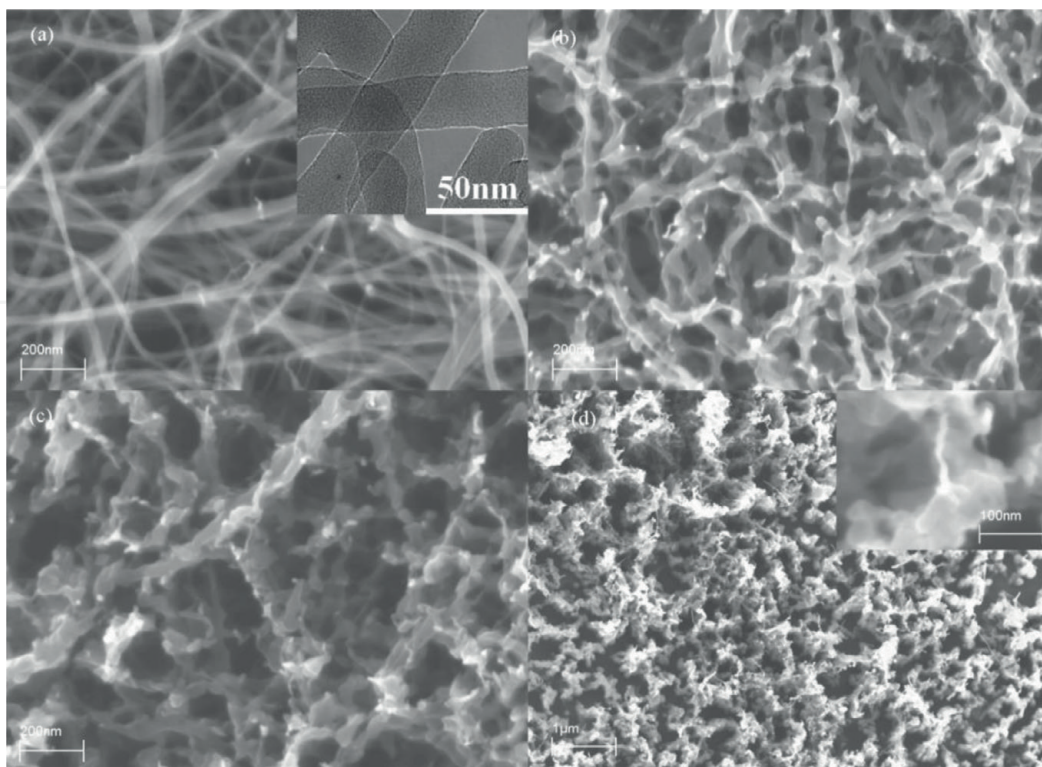


Figure 6.
SEM images of CNTs irradiated by 1.2 keV Ar ions for 15–60 min [23].

the production of a variety of junctions and complicated networks for interconnections of building blocks. A variety of multiple-way junctions and networks of nanotubes and junctions in different shapes of amorphous carbon nanowires have been manufactured successfully by arc discharge method and chemical vapor deposition (CVD) method [24–28]. The center of the junctions prepared by these methods is the location of the metal catalyst. Hydrocarbon-reactive groups are continuously subjected to a process of melting precipitation on the surface of the catalyst and can form these junctions under specific experimental conditions. Therefore, the eradication of metal catalyst nanoparticles may destroy carbon nanotube networks. Furthermore, the effect of the interaction between the nanoparticles with the nanotubes on the properties of devices is not under consideration. Comparing with the arc discharge and CVD, the interconnections of CNTs or carbon nanowires fabricated by ion beam irradiation are by means of the formation of C–C bonds on the surface through the structural reorganization around the defect induced by ions. The various multiple-way junctions and networks of nanotubes or nanowires by ion beam irradiation are interaction of itself, not by means of the metal crystal nanoparticle, which is very important for the development of the miniaturization of electronic and optical electronic devices.

In our previous work [16, 29, 30], the interaction of CNTs and the kilo-electron-volt ion beam has been investigation. The amorphous carbon nanowire network has been fabricated, and the welding of CNTs can also be achieved. **Figure 7** displays the typical SEM and TEM images of CNTs being irradiated by a beam of Si ions. Networks of amorphous carbon nanowires are formed after being irradiated by Si ions. Alterations in the structures of CNTs are found to be initiated after exposure to energetic Si ions which might be due to collision cascade effect that leads to ejection of carbon atoms, and the structure of CNTs is transformed into solid amorphous carbon nanowires at higher beam fluencies. Diameters of amorphous carbon nanowires are uniform, and surfaces are smooth laterally.

The junctions of amorphous carbon nanowire have Y and X type. The amorphous carbon nanowires can form the network by the connection effect of junction. The inset image shows that the thickness of the amorphous carbon nanowire network layer is 0.6 μm and the amorphous carbon nanowire network layer can be detached from CNTs by introducing empty space below it. An empty space between amorphous carbon nanowire networks and CNTs was set up by reducing the space between amorphous carbon nanowires beside the route of ion beam owing to their interconnections.

Figure 8 demonstrates the procedure for fabrication of amorphous carbon nanowire networks in three steps which are based on experimental observation. At first, the atomic network of nanotubes is formed by steady process of amorphization introduced by ion beam irradiation. The energy of an ion is shifted to atoms of the uppermost shell of MWCNTs and leads to produce recoils of several primary carbon atoms and vacancies.

Recoils of energetic carbon atoms will then generate more recoil upon collision with carbon atoms of other shells because of collision cascade effect and hence will add on to the process of damage creation collectively with the ion which further leads to the formation of an amorphous region. When the two nanotubes in overlapping positions are being irradiated by certain fluencies of ion beams, the bond will be formed due to reforming near the irradiation-induced vacancies which may be served as conduit between nanowires and lead to fuse and connect carbon nanowires in form of networks. The carbon atoms in nanotubes are lighter than silicon ions; therefore, a lot of forward carbon recoils will be produced due to collision between the silicon ion and the carbon atoms. In this way, more carbon atoms should be shifted to carbon nanotube films on its inner side where it is distributed loosely.

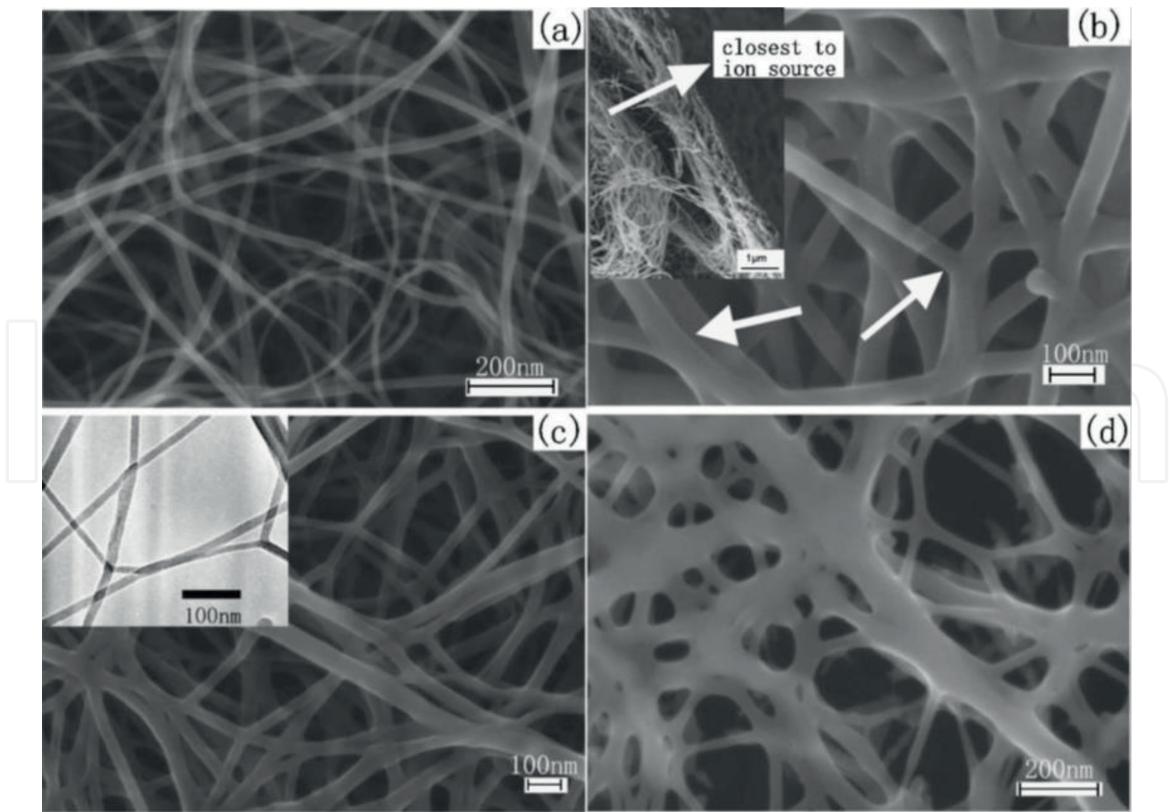


Figure 7.
Images of CNTs (TEM and SEM) irradiated by 40 keV Si ions [29].

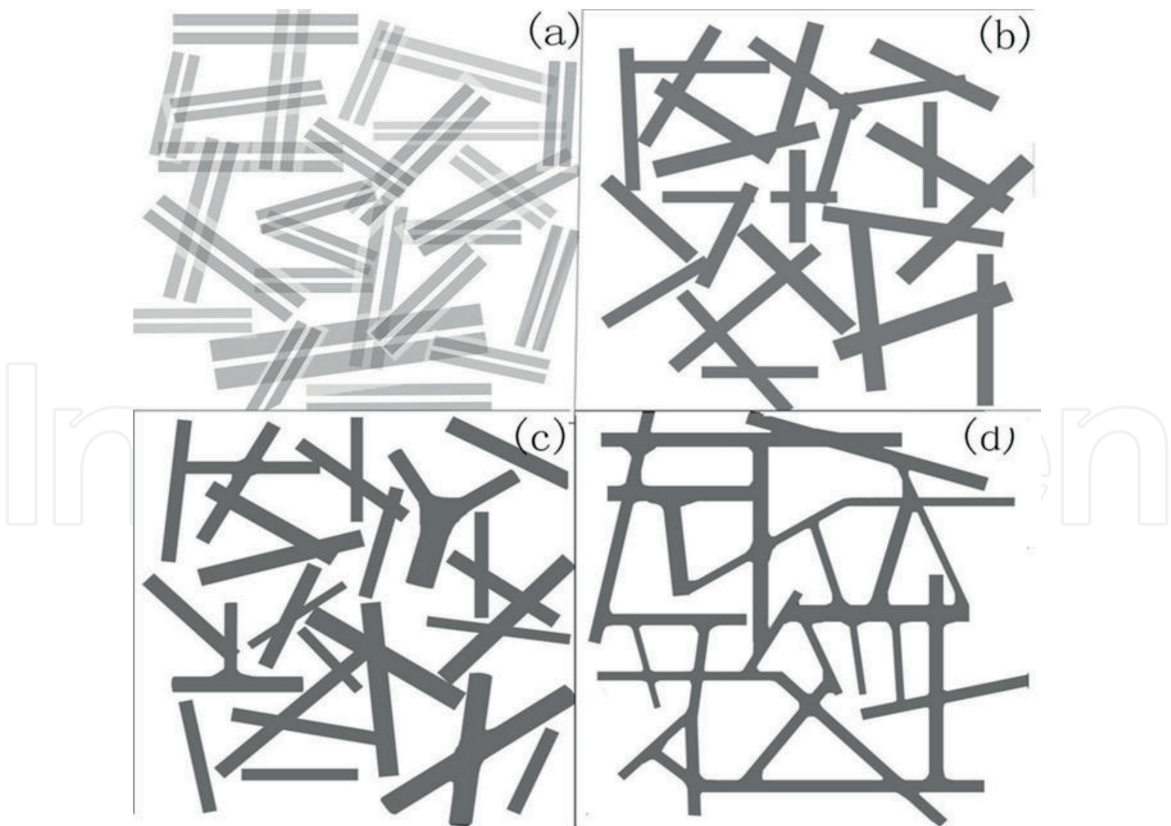


Figure 8.
The process of amorphous carbon nanowire network formation [29].

These carbon recoils will make a bond with vacancies on the surface of CNTs or amorphous carbon nanowires that leads to join or interconnect adjacent overlapped CNTs or amorphous carbon nanowires.

Under the influence of channel effect, a beam of Si ions pushes nanowires or nanotubes near to the ion source to the dense region of carbon material. Due to this process, stacks of carbon nanotubes will become dense, and space will decrease which will be beneficial to fuse the nanotubes. On the other hand, amorphous carbon nanowire networks will unlock the deepest layer of carbon nanotubes which is unapproachable by the beam of ions because of fusion or coalescence of nanowire-induced strains; hence, an empty space is left behind just below the networks of amorphous carbon nanowire.

Eventually, with the increase in fluence of ions to be implanted, a large amount of junctions will be produced that leads to connect the adjacent amorphous carbon nanowires and form the network. With further increase in fluence of ions, sputtering will occur in the thick amorphous carbon nanowire networks, and sputter-induced carbon atoms will be deposited on the surface of network; hence, continuous film will be formed.

Carbon, nitrogen lighter ions, silicon, and argon heavier ions with the same incident energy also have been used to interact with CNTs in order to achieve carbon nanowire network [16]. The morphology change of CNTs shows similar tangency under the irradiation of ion beam of different species with the energy of 40 keV. Carbon nanowire network fabrication occurred in the following steps: (a) local amorphization of nanotubes, (b) fabrication of some simple junctions, and (c) formation of networks.

The irradiation fluencies are differing for forming the nanowire networks of carbon and having different species of ions.

The threshold beam fluence of C, N, Si, and Ar ion for the formation of carbon nanowire networks is 1×10^{17} , 1×10^{17} , 5×10^{16} , and 5×10^{16} ions/cm², respectively. And the corresponding SEM images of carbon nanowire network by the irradiation of C, N, Si, and Ar ion with the threshold dose are shown in **Figure 9**. The carbon nanowire network can be fabricated by the irradiation of different ion beams. Therefore, it is concluded that the formation of carbon nanowire networks induced by ion beam irradiation is a universal technique.

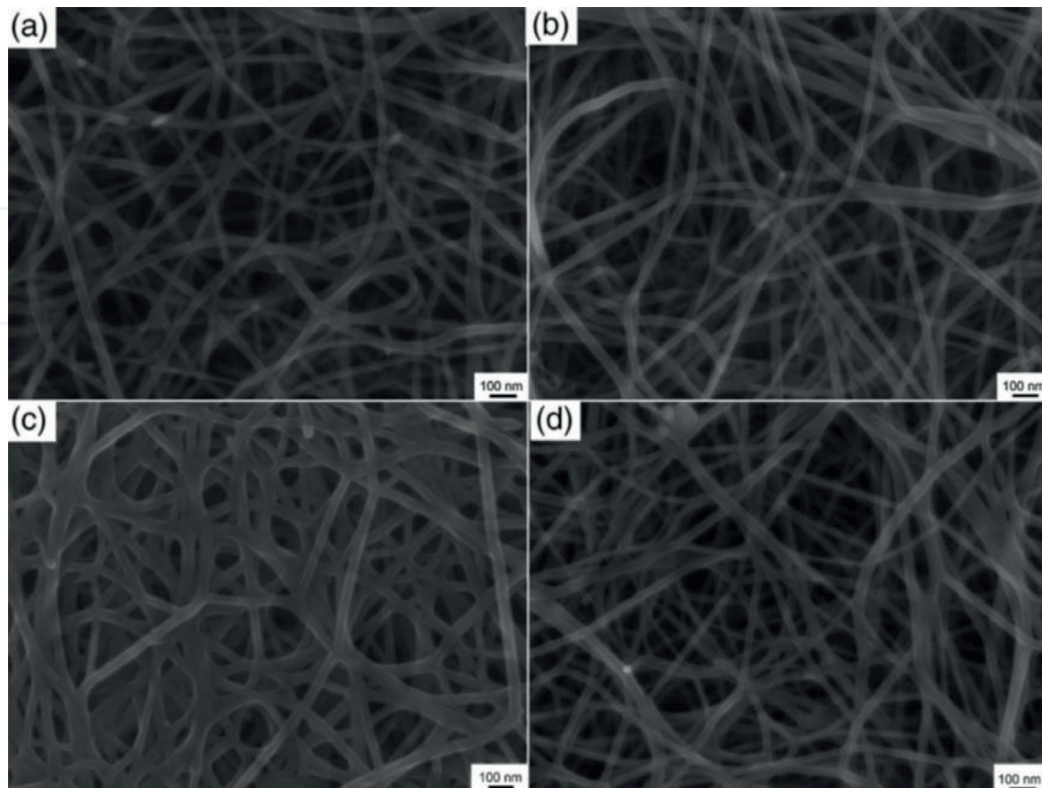


Figure 9.
SEM images of carbon nanowire networks by the irradiation of C, N, Si, and Ar ion with the threshold dose [16].

So far, CNTs are transformed into amorphous carbon nanowire networks after exposure to radiations and not the CNT networks.

The theoretical simulation demonstrated that CNT junctions might perhaps be fabricated only when CNTs are irradiated under the heating conditions [31]. Therefore, the substrate was heated during the irradiation of ion beams in order to achieve multi-walled CNT (MWCNT) junctions [30]. TEM and HRTEM images of MWCNTs after exposure to a beam of Si ions at temperatures ~ 550 and ~ 600 K are represented in **Figure 10**.

At $T \sim 550$ K, irradiated MWCNTs and formed MWCNT junctions are found to have hollow structure, and the carbon nanowires are amorphous carbon structures, but few graphitic layer structures still exist in MWCNTs and formed junctions.

The existence of well-ordered graphitic layer structures is apparent in the irradiated MWCNTs and formed MWCNT junctions, but there is no evidence of existence of hollow structure at $T = \sim 600$ K.

The investigations indicate that the temperature is the main factor in fabrication of well-ordered graphite structure of CNT junctions. The heating temperature is the key factor that improves the rate of defect recombination and easily forms the well-ordered graphite structure, not the amorphous carbon nanowires. **Figure 10** shows the structure of formed MWCNT junctions in detail.

Common graphitic sheets are shared adjacent parts of two MWCNTs and form the MWCNT junction. Moreover, the sum of the thicknesses of the wall “A”

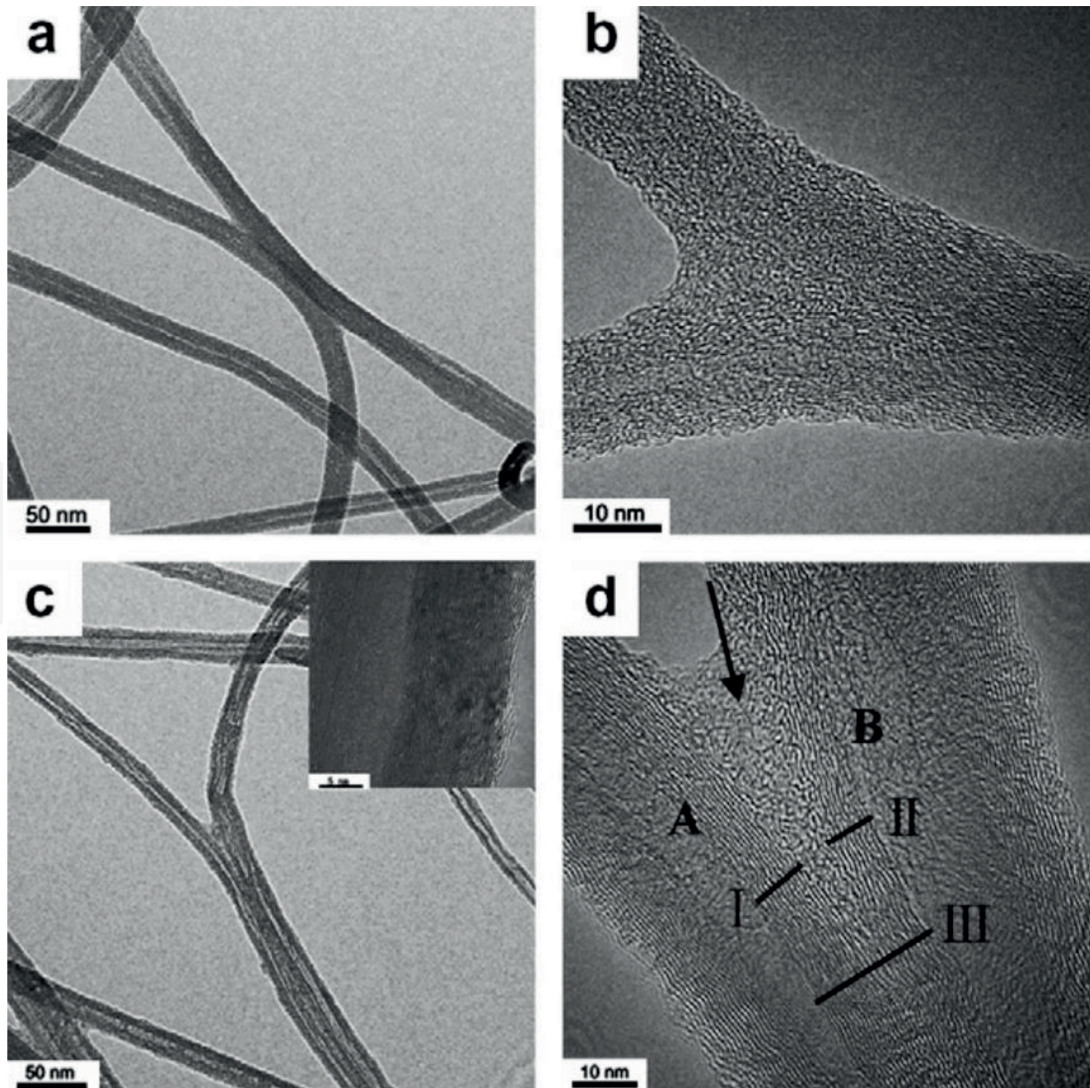


Figure 10. TEM and HRTEM images of MWCNTs being irradiated by Si ions at temperatures ~ 550 and ~ 600 K [30].

(5.5 ± 0.1 nm) and wall “B” (4.5 ± 0.1 nm) is less as compared to the thickness of the junction (11.0 ± 0.1 nm) in the conjoint area of the both MWCNTs as shown in the lines I, II, and III. It is indicated that exposure of MWCNT to radiations at high temperature will form junctions due to self-assembling of sputtered carbon atoms and initiate the process of alteration of disordered graphite lattice to the ordered lattice on outer walls of MWCNTs. Si ion beam irradiation-induced structural transformations in MWCNTs system will make interconnection between MWCNTs, and this process is the same as electron beam irradiation-induced transformations of structure of amorphous carbon to ordered structure of carbon.

It is observed from experimental results that joining of MWCNTs with well-ordered graphitic layer structures is possible at temperature in the range 600–850 K. Except for the effect of heating temperature, the ion dose should affect the welding of CNTs; TEM images of MWCNTs irradiated by Si ion beam with different doses at temperature ~ 600 K are shown in **Figure 11**. There are no junctions at the dose of 1×10^{16} ions/cm². The hollow structure of MWCNTs has vanished with the dose of 5×10^{17} ions/cm², and related HRTEM image shows that both the irradiated MWCNTs and the formed junctions only have amorphous structure.

At low beam fluence, disordered graphite lattices and sputtered carbon atoms might not be sufficient to connect two nearby MWCNTs, and structure of MWCNTs might be spoiled to that extent which would not be cured at high temperature of high radiation dose. Based on the investigation of the experiment,

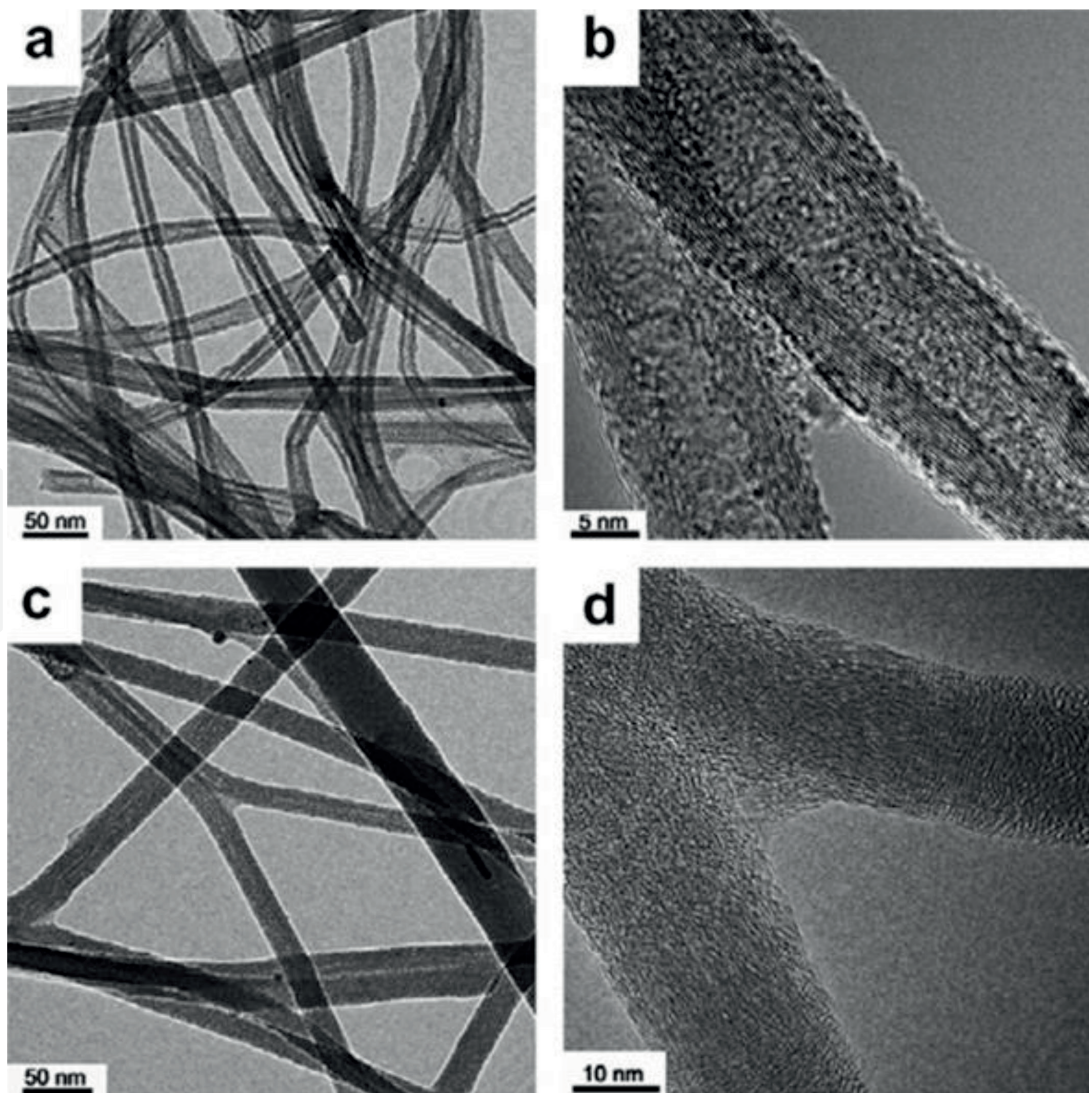


Figure 11. TEM images of MWCNTs irradiated by beam of Si ions with different doses at temperature ~ 600 K [30].

it is stated combination of ion beam irradiation and heating technology can be employed as technique to construct junctions of MWCNTs.

3. Conclusions

In conclusion, “defect engineer” by implantation of ion beam is the main mechanism involved in interaction of CNTs and ion beam. The defect is used to modify CNTs by adding some functional group, functional material, and nanoparticle, and the CNTs should have some complex new properties. The atom and structure near the defect should be reconstructed which leads to the transformation of CNTs; some new carbon nanostructure can be formed such as carbon onion, amorphous carbon nanowire with different hollow structure, carbon nanoparticles, and carbon nanofiber. The reconstruction also can be used to fabricate the junctions of CNTs, form the carbon nanowire networks, and realize the welding of the CNTs.

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