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Chapter 1

Introductory Chapter: Ion Beam Applications

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1. Overview

Ion beam instruments such as particle accelerators, focused ion beams (FIB), and ion implanters are versatile instruments which are broadly applied almost in all field of physics from nuclear physics to particle physics, condense matter physics, and atomic physics. These are also an important tool in other areas of science and technologies such as chemistry, environment sciences, biology, space science and engineering, and semiconductor technology. Its applications are substantially being extended for generating cluster ions, synchrotron radiations, focused ion beams with molecular nitrogen source gas, and proton-proton colliders. Progress in nuclear and particle physics originated from studies with ion beam is playing now a determining role in astrophysics and cosmology. Similarly, low energy ion beam, such as ion implanters and FIB, are also useful instruments for device fabrication and microscopy.

This chapter aimed to present a brief review of a broad range of applications of the ion beam in diversified fields which will be useful for the common reader to understand ion beam science and technology. Finally, the latest research using MeV ion beam, focused ion beam, and ion implanter is compiled in this book in three respective sections. For a further concise review of ion beam applications, electron beams are excluded from this review chapter and book, even though electron microscopes and other useful applications are being emerged in different areas of fields. For example, focused electron beam was used in patterning and cutting of nanowires [1]. **Figure 1** shows the patterning of ZnO nanowires using focused electron beams at transmission electron microscopy (TEM).

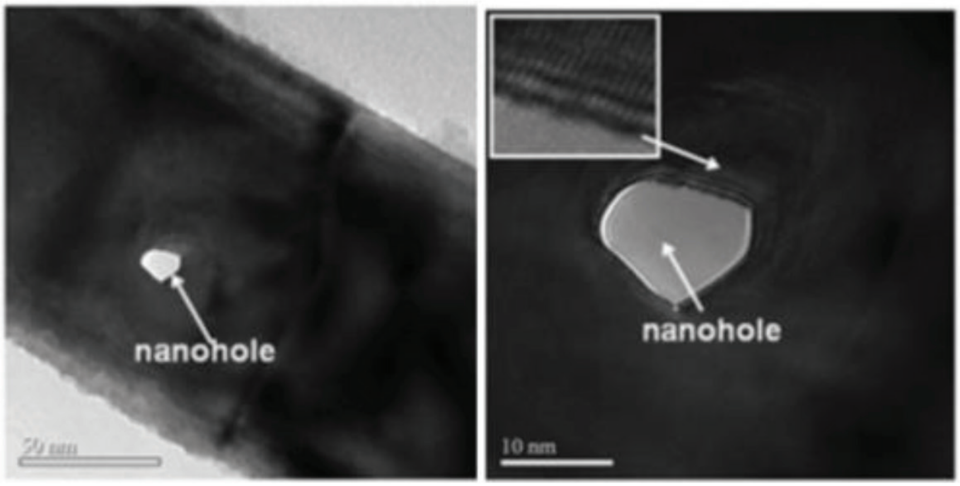

Figure 1. Focused electron beam to create nanoholes in ZnO nanowires [1].

2. Applications

2.1. Materials science

This section introduces to the materials scientists, chemists, and physicists about the ion beam techniques for materials analysis, modification of materials, and development of new materials using ion beam. MeV ion beams for materials analysis techniques are being used as complementary techniques in materials analysis. These are the group of non-destructive analytical techniques such as particle induced X-ray emission (PIXE), particle-induced gamma-ray emission (PIGE), nuclear reaction analysis (NRA), Rutherford backscattering (RBS), and ion channeling, which are being used to analyze composition and depth profiling of solids. Almost all elements from hydrogen onward can be probed by ion beam analysis (IBA). IBA techniques are discussed in detail in Section 2. Focused or collimated beam into micron and submicron (Microprobe) is now developed, which is useful for mapping of lateral elemental distribution over a specimen. These microbeams are useful for high-resolution imaging by measuring density variations through scanning transmission ion microscopy (STIM) technique.

Ion beam modification of materials is an important application of ion beam. Recently, boron carbonitride nanotubes were synthesized from boron nitride nanotubes using C ion beam irradiation [2]. Similarly, phase transformation of thin film and nanostructured materials by ion beams is another important application. Ion beam-induced controlled modification of physical properties is possible in thin film and nanostructured materials [2–8]. Phase segregation and separation is another unique application of ion beam [9].

Ion implantation is an exceptional surface treatment method to implant N-type and P-type dopants into semiconductors to make solid-state electronics. Moreover, dilute magnetic semiconductor devices could be synthesized through direct implantation of magnetic elements into nonmagnetic semiconductors [10, 11]. After developed FIB, now it is also possible to implant required elements into required depth to make semiconductor devices. Section 3 describes the advantages of ion implantation process with emerging new applications.

Focused ion beam in keV energies is also used for microscopy of materials [12]. FIB instrument can be utilized for microstructure tomography in the range from ~100 nm to 10 μm. Advanced FIB microscopy has been described in detail in Section 3.

2.2. Environmental sciences

IBA techniques such as PIXE are widely used for environmental studies. Trace element measurement in aerosol samples is an important application of MeV ion beam. After developed microprobe, now it is possible to measure or mapping of heavy metals in various samples like trees, fish, deposit mining dust on trees leaf, glacial melting study, etc., which give valuable seasonal and historical information of pollution to the particular area of study. Many authors have proven the diagnostic usefulness of hair analysis in assessing pathological elemental concentrations in the body. Hair has been shown to reflect environmental and occupational exposure to lead, mercury, aluminum [13], and a combination of multiple metals. Microanalysis of hair to assess the toxic metals in scalp hair of artisanal miners are important environmental studies using micro PIXE. The PIXE technique has been proven as a high accurate, sensitive, and nondestructive method to determine concentration and composition of chemical elements. Beside these, PIXE technique has been successfully used in many other environmental studies like elemental mapping, source appointment, and chemical characterization of various pollutants.

2.3. Device fabrications

Focused ion beam either in MeV or keV energies is a considerable tool in science and technology for micro and nanodevice fabrications using both bottom-up and top-down approaches. In the bottom-up approach, individual nano-objects such as nanowires and nanotubes can be assembled directly together in form of functional welded networks using ion beam induced nano-welding technique. Ion beam-induced nanowelding is another option to make nanowire/nanotube-welded junctions and to make nanodevices or integrate nanodevices. Recently, researchers used ion beam as a tool to weld carbon nanotubes, silver nanowires, Ni nanowires, and SiC nanowires to make junctions and large-scale welded networks [14–21] (**Figure 2**).

In top-down device fabrication approach, 3D MeV proton beam writing is an important technique to make micro and nanodevices [22]. Whereas, keV energy FIB is now an essential tool to use for TEM sample preparation and device fabrication and to fabricate complex nanoscale structures/patterns. It is a tool that directly makes a 3D and 2D pattern without masks from a few nanometers to hundreds of micrometers in size. Compact FIB instruments are developed and being used to fabricate microelectromechanical systems (MEMS)-based devices, microfluidic chips, photonic devices, and DNA sequencing nanopore membranes [23, 24]. More detail FIB applications are described in Section 3.

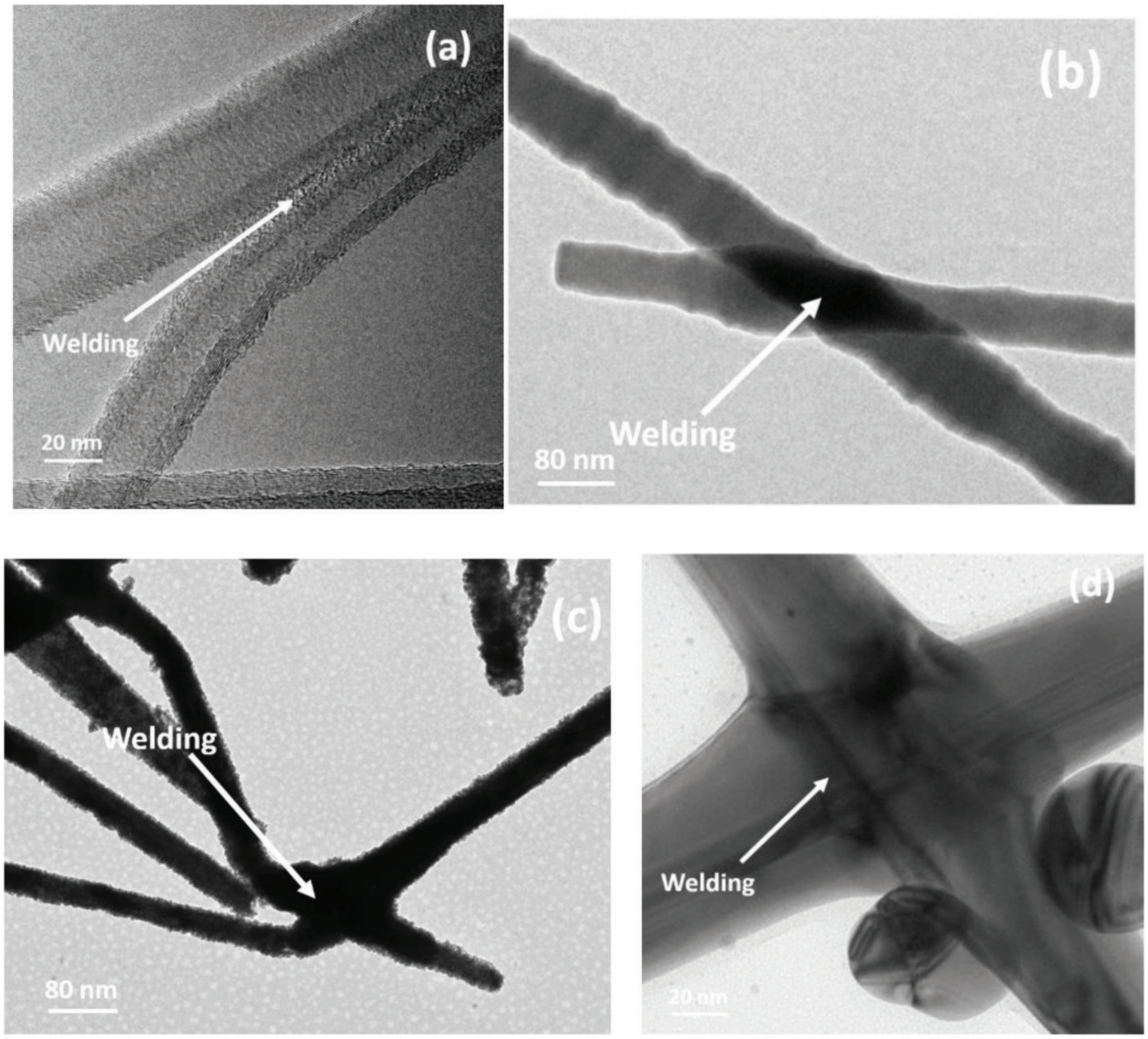

Figure 2. Ion beam-induced welding of (a) multiwalled carbon nanotubes [21], (b) SiC nanowires [14], (c) Cu nanowires, and (d) silver nanowires [18].

2.4. Atomic physics

Excitation and ionization of atoms by ion beam is another application of ion beam technology to study atomic structure. Ion beam-induced X-ray emission is a rich phenomenon to study the complicated process during ion beam interaction with matter. The fundamental parameter such as ionization cross section is a pure quantum mechanical phenomenon. When an ion passes through the target atom, the target atom becomes ionized due to columbic interaction of ions with target atom. The target atom is ionized by absorbing ion beam energy and rest of the energy is utilized in ejaculation of auger electron in case of atomic collision and heating.

When an atom deionized, it released the absorbed energy in the form of photon, and its excess energy ejaculates the auger electron and rest of the energy loss goes in the heating of sample. The probability of emission of x-rays or photon from particular due to electron transition from upper shell to lower shell is called the fluorescence of particular shell. We can measure the

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X-ray production cross section of particular shell using fluorescence yield of shell of target element. For K-shell, X-ray production cross-section data are available so far to support PIXE technique for materials analysis, whereas a lot of discrepancies exist in L-shell and M-shell of X-ray production cross section measurement. As it had become complicated due to fluorescence and auger electron transition between levels and sublevels.

The fine and hyperfine lines originating from s, p, d and f orbitals and its suborbitals (from levels and sublevel) can be studied and explore the fluorescence and auger electron transition and Coster-Kronig transition for L- and M-shell X-ray production cross section. The relative intensity ratios of K-shell, L-shell, and M-shell transition lines can be explored from light and heavy ion in advanced studies. Decreasing and increasing trend of intensity ratio of transitions lines $K\alpha/K\beta$ and $L\beta/L\alpha$ can also be explored as a function of ascending order of elements Z, respectively.

The stopping power or energy loss of projectile in the matter is another research area. Due to lack of correct knowledge of stopping power, error in cross-section measurement is large. Bethe formalism and Ziegler, the founder of TRIM/SRIM software for heavy ions stopping power, may deviate from the experimental results at different energy ranges. The study reveals that there are many discrepancies exist in the theoretical models. Using heavy ion for cross section and stopping power studies can improve the theoretical models.

The multi-ionization effect by heavy ion is an open research field and a once need to explore the complicated physics exit behind it. PIXE using heavy ion lead us to find the fact for corrections of theoretical Models.

2.5. Nuclear physics

Study of nuclear structure and nuclear reaction using ion beam is another application of ion beam technology. As the diameter of the nucleus is less than 10^{-14} m, the nuclear structure study with microscopy technique is hard to investigate. Therefore, high energy ions which have a size comparable to a nucleus are another option to investigate the structure of the nucleus. Scattering cross section could be measured by energetic ions interacting with target nucleus. Ion-induced nuclear reaction could be possible to emit secondary particles such as neutrons, alpha particle, gamma-rays, and beta particles. Once energies and angular distribution of secondary particle emission observe, then size and shape of the nucleus and the forces existing inside the nucleus could be deduced. Large range of ion beam-induced nuclear reactions is possible.

Proton beams with different energies are very useful for various aspects of research, such as proton beams with energies between 1 MeV and 1 GeV are almost always used for nuclear structure studies. Proton beam with energy between 1 and 100 MeV could be made to interact with whole nuclei or with several nucleons, while proton beam with energy between 100 and 1000 MeV could be interacted with individual nucleons in the nucleus which giving more precise information about each nucleon. Ion beam energies greater than 1 GeV are useful to produce short-lived particles such as mesons [25].

2.6. Biology

Ion beam could be applied in biology for probing, damaging and modifying the biological samples. Ion beam accelerators have advanced further by the introduction of nuclear microprobes. These microprobes have opened up new areas of research in biological science by allowing elemental microanalysis, with imaging capabilities, particularly suitable for the measurement of trace elements in biological tissues. Whereas ion beam-induced mutation of crops, vegetables and fruits are matured method. Micro PIXE is continuously applied in life science for comprehensive food crops analysis to determine traces of toxic heavy metals.

2.7. Particle physics

High-energy ion beams produced by particle accelerators also have vast applications in particle physics as it is a tool to study extreme states of matter. In high energy physics, particle colliders have taken part in a key role in scientific discoveries for last many decades. Particle colliders are basically ion beam accelerators where particles are accelerated up to relativistic speed to collide with a stationary target or head-on collision with each other like proton-proton colliders. At sufficiently high energy, relativistic particles smash into other high energy particles. Energies of the colliders continuously increase over time for exploring new physics/particles. Moreover, advanced high energy particle detectors are being developed for understanding the properties of high energy particles such as mass, energy, charge, spin, and isospin, which are being created during collision of relativistic particles.

Large Hadron Collider (LHC) is the world's largest accelerator built at Swiss-French border in Geneva, Switzerland. It is also used to accelerate the heavy ion beams. It is capable of accelerating Pb ions with the beam energy of 2.76 TeV/nucleon, which yield to 1.15 PeV in total, with the luminosity of 1.0×10^{27} cm^{-2} s^{-1}. Heavy ion beam focuses on study of quantum-chromo-dynamics (QCD), the strong interaction sector of Standard Model (SM). It allows to study physics of strongly interacting matter and the quark-gluon plasma at extreme values of energy density and temperature in nucleus-nucleus collision.

2.8. Medical application

Medical radioisotopes for medical applications are well established for diagnostic and therapy. Ion beams are also being used to produce radioisotopes that are used for the mentioned uses. Further research is also going on to produce high-quality radioisotopes through the series of investigation into production of radioisotopes and its decay characteristics in medical applications such as cross-section measurement of ion beam with target atom to monitor nuclear reactions, compilation of nuclear reaction data for therapeutic radionuclides production, and Beta decay nuclear reaction cross-section measurement for positron emission tomography.

Ion beam therapy is another unique application of ion beam, which provides cutting-edge cancer treatment. Ion beam therapy is a newly emerging treatment for cancer, which is more effective than any other old techniques. In ion beam therapy, ion beam is offering the possibility of excellent dose localization and thus maximizing cell killing within the tumor. Proton therapy for cancer treatment is a matured technology to damage cancer cells while producing the least

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damage to the surrounding uninfected tissues. Radiotherapy with carbon ion beam is also developed and is popular in the world, while heavy ion therapy research is going on by understanding fundamental damage mechanisms of cancer cells under heavy ion irradiation [26].

2.9. Nuclear astrophysics

The production of radioactive ion beam and studying its properties are currently a hot research area in accelerator scientific community and for nuclear astrophysicists. Energetic radioactive ion beam, a beam of short-lived nuclei, opens up a new research direction to study nuclear reactions and nuclear structures. Nuclear reaction with radioactive ion beam provides information on reactions that occur at our sun and other stars in our universe. For astrophysics point of view, scientists have produced short-lived halo nuclei in radioactive ion beam facilities to study nuclear astrophysics. Further research is going on for a generation of short-lived neutron-enriched nuclei in next-generation radioactive ion beam facilities, which are required to understand the existence of heavy elements in the universe by the astrophysics rapid neutron-capture process. Through this short-lived radioactive ion beam, it may be possible to explore the secrets of the universe as these nuclei beams play a vital role in understanding the origin of the elements and the dynamics of stellar objects. Moreover, short-lived nuclei (radioactive ion beam) are essential for useful studies of astrophysical objects such as neutron stars, super novae, X-ray bursters, and supernovae. In conclusion, short-lived halo nuclei in radioactive ion beam facilities will provide us with the information that how the chemical elements had formed our world in the cosmos [27].

3. Conclusion

Recent researches in ion beam applications that are mentioned in this introductory chapter are so detailed that it is not possible to cover them in this book. Therefore, this book only has selected special chapters from distinguished authors that cover various aspects of:

1. MeV ion beam applications
2. Focused ion beam applications
3. Ion implantation

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