Carbon Nanotubes under Electron Irradiation
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- Nano-engineering of carbon nanotubes under the electron beam: structuring, welding, bending, etc.
- Shrinkage and deformation of nanotubes under electron irradiation
- Nanotubes as deformation/extrusion cells on the nanoscale
- Growth of nanotubes by injection of carbon atoms into metal crystals

In-situ experiments in the TEM
Irradiation and imaging of nanotubes at the same time and at the atomic scale

Electron irradiation:
- atom displacements by energetic electrons
- structural rearrangement of nanotubes
- transfer of interstitials into the central hollow of tubes

High specimen temperatures:
- annealing of irradiation defects
- high mobility of interstitials and vacancies

Imaging and manipulation of nanotubes:
- both at the atomic scale
- at the same time

Irradiation effects in the nanotube lattice
Low temperatures → defect agglomeration
High temperatures → annealing of defects (> 300°C)

Threshold energy of electrons to displace atoms:
- Multi-wall nanotubes: ~ 100 keV
- Single-wall nanotubes: 80 keV

Defect evolution in carbon nanotubes
Carbon nanotubes under an electron beam:
- Generation of interstitials: highly mobile, vanish preferably into the central hollow
- Vacancies: mobile, coalesce and form immobile divacancies

Restructuring of a defective nanotube (simulation by A. Krasheninnikov)
- Closure of dangling bonds
- Shrinkage under irradiation

- Single vacancies coalesce to form divacancies
- Divacancies close by saturation of dangling bonds
- Formation of non-six-membered rings
- Reduction of surface area → shrinkage or bending of tube
- High strength of graphitic network remains, even when defects prevail

Metal nanowires inside collapsing nanotubes:
Nanotubes as high-pressure cylinders and extrusion cells

Encapsulation of metal nanowires in carbon nanotubes:
- Collapse of tubes under electron irradiation
- Deformation of metal wires (thinning, defect formation)
- Extrusion of metal wires

Growth of nanotubes under the electron beam

- Carbon atoms are ingested by the electron beam into the metal core of the host nanotube.
- When the end face of the metal is round, a hemispherical graphene cap forms and serves as the starting point for nanotube growth.
- A new nanotube grows from steps on the metal surface. Carbon atoms are fed from the metal crystal.

Evolution of nanotubes under electron irradiation
- Nanotubes act as pipelines for the transport of interstitial atoms
- Stability of nanotubes increases with their diameter

Cuts of SWNT bundle by focused electron beam:
- Open ends close by fullerenic caps
- Closed nanotubes inside the tubes
- Carbon atoms in the tubes are reduced by caps
- Formation of reflected atoms at second cut
- Second cut requires higher electron dose than first cut

Cutting of a single-wall nanotube by electron beams:
Diffusion of interstitials in carbon nanotubes

Second cut requires higher electron dose than first cut

Cutting of SWNT bundle by focused electron beam:
- Open ends close by fullerenic caps
- Closed nanotubes inside the tubes
- Carbon atoms in the tubes are reduced by caps
- Formation of reflected atoms at second cut
- Second cut requires higher electron dose than first cut
- Annealing of reflected atoms at second cut
- Diffusion of interstitials in nanotubes increases with temperature and distance to the first cut
- Information about migration barrier for C atoms in tubes: ~ 0.3 eV

Shrinkage and deformation of metal wires
- Collapse of tubes under electron irradiation
- Deformation of metal wires (thinning, defect formation)
- Extrusion of metal wires

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