To turn wound growth to layer-by-layer growth we may play now a number of tricks:
- adsorb a gas to step edges that lowers $\Delta E_5$ ($\Rightarrow$ increase $L$)
- lower temperature or increase flux in the nucleation stage of each deposited layer ($\Rightarrow$ decrease $\lambda$)
- make an artificial high density of nuclei at the beginning of each layer ($\Rightarrow$ decrease $\lambda$)

To Ion Beam Processes

Energetic particles are a very efficient tool to fabricate nanostructures and to analyze them. The most simple way to give a well defined energy to atoms is to ionize them and to accelerate them subsequently through electrical fields. The energy range provided by various ion beam sources ranges from a few eV to GeV. As we are interested in surfaces and nanostructures, our focus is on low energy ions, where low ranges from 10 eV - 10^5 eV.

To describe the interaction of energetic particles we use the concept of differential energy loss or stopping power of a thin layer with thickness $dx$ of the target

$$\frac{dE}{dx} = \left( \frac{dE}{dx} \right)_n + \left( \frac{dE}{dx} \right)_c = -N \left[ S_n(E) + S_c(E) \right]$$

$(\frac{dE}{dx})_n$ is the nuclear stopping power due to elastic collisions between the particle and the nuclei of the target. If the transferred energy $T$ exceeds a threshold value $T_0$, the displacement energy, a lattice atom is removed from its site and creates a vacancy - in initial pair.

$(\frac{dE}{dx})_c$ is the electronic stopping power due to inelastic interactions between the bombarding particle and the electrons in the solid. They lead to excitation, ionization, transfer or exchange of electrons in the
in the target. Electronic losses only take place for charged particles (or atoms composed of charged particles). In metals electronic losses quickly turn up as heat, i.e. the electronic excitations couple to lattice vibrations (electron-phonon coupling). In insulators electronic losses may induce permanent property changes (Ian tracks - see below).

In (E) N is the density of atoms in the target (atoms/volume), S_{m}(E) is the nuclear stopping cross section and S_{e}(E) is the electronic stopping cross section. As shown in here, the electronic stopping cross section has a maximum at very high energies in the 10 MeV range. For light particles it dominates even at low energies.

The nuclear stopping cross section shows a maximum in the range of 50 keV for medium mass elements. The nuclear stopping cross section can be written as:

\[ S_{n}(E) = \int_{0}^{T_{max}} T \cdot \frac{d\sigma(E, T)}{dT} \cdot dT \]

where \( T_{max} = \frac{4N_{1}N_{2}}{(N_{1} + N_{2})^2} \cdot E \) is the maximum transferable energy in an elastic head-on collision, \( d\sigma(E, T) \) is the differential cross section, i.e. the cross section for an energy transfer in \([T, T+dT]\) for a particle of energy \( E \). Conservation of energy and momentum define a unique relation between scattering angle \( \Theta \) and kinetic energy \( T \). This relation (and thus \( d\sigma(E, T) \)) is determined by the interaction potential of the particles. For energy well above the binding energies (\( \approx 1 \text{eV} \)) the interaction may well be described by a
screened Coulomb potential

$$V(r) = \frac{Z_1 Z_2 e^2}{r} \phi \left( \frac{r}{\alpha} \right) \quad \text{(universal potential)}$$

where $\phi \left( \frac{r}{\alpha} \right)$ is the screening function and $\alpha$ the screening length. The function $\phi$ is parametrized and depends on the particle/target combination. For very high ion energies, the interaction potential approaches the Coulomb potential and does becomes the Rutherford scattering cross-section. Electronic stopping causes very little scattering of the primary ion, but essentially only energy loss. Due to the energy loss, an incident ion has a finite range in a solid. The average path length or ion range can be derived from the stopping cross-sections

$$R(E) = \int_{E}^{0} \frac{dE}{\frac{dE}{dx}} = -\frac{1}{N} \int_{E}^{0} \frac{dE}{S_n(E) + S_e(E)}$$

$$= \frac{1}{N} \int_{0}^{E} \frac{dE}{S_n(E) + S_e(E)}$$

The projected range $R_p$, i.e. the projection of the path length on the direction of incidence, and the penetration depth $x$ (compare Fig 7.3) are readily available, but can only be approximated analytically.

When an energetic ion hits a surface and penetrates into it, the ion transfers energy to atoms of the solid. As long as the transferred energy $T > T_d$ ($T_d \approx 20$ eV) the atom is set into motion and may itself collide with other atoms. This way a tree of colliding and moving atoms is generated, the collision cascade. Due to the complex collision sequences, atoms in the collision cascade may also move backwords, towards the surface.
Such particles arriving at the surface may leave the crystal, if their kinetic energy at the surface is sufficient to surmount the surface binding energy $U_0$, which may be approximated by the cohesive energy. The number of energized atoms moving towards the surface must be proportional to the deposited energy close to the surface. Thus for the sputtering yield

$$Y = \frac{{\text{sputtered (removed) atoms}}}{{\text{per incident ion}}}$$

we obtain

$$Y \sim \frac{{N \cdot S_n(E)}}{{U_0}}$$

We discuss now two effects of ions etching a solid:
- implantation = the ion comes to rest in a penetration depth $x$
- sputtering = atoms are removed from the solid's surface.

An efficient way to calculate implantation and sputtering is using Monte Carlo simulations in the binary collision approximation. Programs for these calculations are freeware, e.g. SRIM.

The key assumption in these programs is that it is sufficient to consider only binary collisions between two atoms. The target is amorphous with random atom positions. The interaction is described by the universal potential and electronic stopping is taken into account. Fig 7.4 right shows a collision cascade calculated by TRIM. The accuracy of TRIM is not perfect; sputtering yields may be off by up to a factor of 2 due to uncertainties in stopping power.

However, we do not yet have the full picture of the ion-solid interaction. To understand on the atomic scale it is not sufficient to stay with the picture of the binary collision. In this picture we would be left with pairs of displaced atoms and vacancies,
which may recombine with interstitials depending on temperature

However, this is not the entire truth. When the collision energies decrease, the binary collision approximation breaks down. The energy is distributed among all atoms in a small volume, such that all atoms are in motion there. Equipartitioning of potential and kinetic energy takes place. We obtain a nano volume of molten material. This effect is called thermal spike. As a liquid has usually a greater volume than a solid, a shock wave is generated propagating outward and melt flows onto the surface. The spike temperature decreases by phonon emission and the liquid volume starts to recrystallize. The dilated melt moves inward such that eventually one or several droplets remain in the center of the previous liquid. Fig. 7.5 displays the shockwave as obtained by a molecular dynamics simulation and the pair correlation function of the melt area at two times compared to the one of a liquid. Figs. 7.6 and 7.7 are movies of an MD simulation of a 16 keV Ar⁺ ion impact on Au (111). Fig. 7.8 shows stills from a 10 keV Au → Au(111) simulation and STM topographs from 10 keV Xe⁺ → Pt (111) impacts.
Fig. 7.9 summarizes the stages of ion-solid interaction. From the observations of the molecular dynamics simulations we note that the formation of the liquid induces very efficient mixing of the atoms (displacements per damage energy unit and atom). Moreover, due to recrystallization, the damage is inhomogeneous with a central vacancy core and distributed interstitial.

We are now ready to discuss applications in nanotechnology:

- **Implantation**
  - Ion implantation is a standard technique to create dopant layers in semiconductor devices. The ion energy determines the depth of the dopant layer (B, P, As); after implantation, the damage needs to be healed by a thermal treatment. Virtually all devices possess implanted dopants.

- **Reso tox and cluster formation**: Implantation to a high concentration of a species able to create a second phase allows one the formation of a buried epitaxial layer.

\[
\text{e.g. } \text{CoSi}_2 \quad \text{NiSi}
\]

The movie visualized in Fig. 7.10 shows the annealing process for a narrow stripe of material. Fig. 7.11 displays the comparison of MD simulations and experiment for Si–Nano cluster formation through 1 keV Si–implantation. The nano-clusters were considered to replace the floating gate in flash memories. Also, the SIMOX is an alternative technology:

- **Smart cut** is a new technique to create single-crystalline thin Si layers on oxide. In technology such thin active layers reduce parasitic capacities of devices. IBM and AMD use silicon on oxide in their products. The method is paired with implantation of an insoluble gas, e.g., H, He.
The gas precipitates in the form of small bubbles. Pumping in more gas overpressurizes the bubbles so strongly that a crack forms and a thin layer can be split off.

A beautiful application of smart cut to nano structure formation results from wafer splitting, tilted or twisted rebonding and subsequent thermal annealing. As the TEM images of Fig. 7.13 shows, highly regular arrangements of dislocations result. Through etching and subsequent deposition, fairly regular quantum dot lattices may be grown.

**2. Sputtering**

- **SIMS** meaning Secondary Ion Mass Spectrometry is a method to perform tomographic. A fine beam of ions ($\phi = 100\, \text{nm}$) is scanned over the sample. The sputtered atoms are analyzed in a mass spectrometer. By sputtering the scanned area is eroded and not only lateral but also depth resolution (about 1-2 nm) is achieved. With SIMS concentrations in the part per billion ($10^{-9}$) range may be achieved.

- **FIB** meaning Focused Ion Beam is similar to a Scanning Electron Microscope. Its key element is a liquid metal ion source. Liquid metal is coating a sharp tip at high positive potential. It forms a so-called Taylor cone. At the tip due to the enormous field strength the metal atoms are field ionized. Due to the coherence of the ion beam (all ions shot with the same energy and come from a very small spot) a very fine ion beam (a few nm $= \phi$) can be formed. It can be used as a nano drilling and milling machine. The secondary electrons emitted where the ions hit the sample allow imaging. See Figs. 7.13 - 7.17. Show the FIB method and applications.

- **Pattern formation** Under ion erosion surfaces self-organize into patterns. Fig. 7.13 displays as examples self organization of GaSb and Si(001). Characteristic wavelengths or dot separations are of the order of 50 nm.