Physical Vapor Deposition (PVD)

- Thermal evaporation
- E-beam evaporation
- Knudsen cell, Effusion cell
- Molecular Beam Epitaxy (MBE)
- Sputtering
- Laser ablation
Thermal evaporation

Knudsen cell

Covers substrate features like snow. Polycrystalline films.

Boat

Coil

Titanium Sublimation Pump (TSP)

This is a kind of getter pump

http://www.lesker.com/newweb/vacuum_pumps/ionpump_gamma Ionpump_tisub.cfm
Hot and clean.
Evaporation boats made from strong metals.

Thermal vacuum evaporation (resistance evaporation) is a coating method used as part of the PVD process (Physical Vapor Deposition). The material that is to form the subsequent layer is heated in a vacuum chamber until it evaporates.

The vapor formed by the material condenses on the substrate and forms a coating. Because many coating materials react with water, nitrogen and oxygen, they are performed in a high vacuum. The high temperatures that are required are generated using resistance heaters or, in some cases, induction heaters, electron beam evaporators, or, if necessary, plasma spray electrodes. Evaporation boats are made from refractory metals such as molybdenum to help them withstand the high temperatures caused by the coating material.

Which boat is right for your coating material?
Are you looking for the right evaporation boat for your coating material? Boats with one plus are generally suitable for your material. Boats marked with two pluses are particularly highly recommended. Would you like to find out more? Let’s talk in person.

Our metals for vacuum evaporation.
We produce boats designed to hold the material for evaporation. These are available in various shapes and dimensions and are used in a wide variety of applications.
Electron-beam evaporation

http://www.polyteknik.com/E-Beam_Evaporation.html
<table>
<thead>
<tr>
<th>Element</th>
<th>Symbol</th>
<th>Melting Point °C</th>
<th>Density (bulk, g/cm³)</th>
<th>Z-ratio</th>
<th>Temperature°C @ Vapor Pressure (Torr)</th>
<th>Evaporation Method</th>
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<td>490</td>
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<td>0.336</td>
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http://www.cleanroom.byu.edu/TFE_materials.phtml
Electron-beam evaporation

http://www.eps.hw.ac.uk/institutes/photonics-quantum-sciences/mba.htm
http://www.fkf.mpg.de/273938/30_Oxide_MBE_Lab
Electron-beam evaporation

Electron accelerating voltages: 3 kV – 40 kV

10 - 100 kW power

High vacuum

x-rays and secondary electrons are emitted

deposition rate from 0.1 μm / min to 100 μm / min

Alloys can be difficult because the components evaporate at different rates

Co-evaporation is sometimes used for alloys

line-of-sight deposition process

Not suitable for large areas or coating complex shapes
Shadow evaporation
Single electron transistor
Molecular Beam Epitaxy (MBE)

http://lase.mer.utexas.edu/mbe.php
RHEED
(Reflection high-energy electron diffraction)

http://en.wikipedia.org/wiki/Reflection_high-energy_electron_diffraction#mediaviewer/File:RHEED.svg
Molecular dynamics

Figure 6.8 Terrace step kink (TSK) growth model of epitaxy: growth proceeds at kinks, and adatoms on flat surface diffuse to energetically favorable positions at kinks. Wafer miscut creates terraced structure. Reproduced from Jenkins (1995)

Calculate the motions of the atoms at the surface.
Growth modes

Figure 1. Cross-section views of the three primary modes of thin-film growth including (a) Volmer–Weber (VW: island formation), (b) Frank–van der Merwe (FM: layer-by-layer), and (c) Stranski–Krastanov (SK: layer-plus-island). Each mode is shown for several different amounts of surface coverage, $\Theta$. 

Evaporated atoms or molecules may form layers, needles, or clusters.
**Figure 6.6** Thin heteroepitaxial $\text{Si}_{1-x}\text{Ge}_x$ layers for high-speed bipolar transistors. The hatched layers are graded epilayers with constantly changing germanium content.
Strain induced by lattice mismatch

\[ \varepsilon_\parallel = \frac{a_{\text{SiGe}} - a_{\text{Si}}}{a_{\text{Si}}} \]

extra net plane

direction of slip

dislocation core
TEM image of a 3 nm Si cap/ 15 nm SiGe 50% /10 nm strained SOI structure grown at CEA-Leti and used for p-SiGe MOSFET fabrication.

http://www.fz-juelich.de/pgi/pgi-9/EN/Forschung/08-strained%20silicon/04_Biaxially%20strained%20Si_SiGe_%28S%29SOI%20heterostructure/_node.html
MODFET (HEMT)

Modulation doped field effect transistor (MODFET)
High electron mobility transistor (HEMT)

\[ V_T = \text{Threshold voltage} = \text{voltage where charge is depleted} \]
Heterostructure

pn junction formed from two semiconductors with different band gaps
**HEMT:** HEMT devices are found in cell phones, electronic warfare systems, microwave and millimeter wave communications, radar, and radio astronomy.

PhD Thesis Sergey Smirnov
http://www.iue.tuwien.ac.at/phd/smirnov/node71.html

\[ R_K = \frac{h}{e^2} = 25812.807557(18) \, \Omega \]
Quantum Hall Effect

\[ \rho_{xy} = \frac{-B_z}{ne} = \frac{h}{ve^2} \]

\( v = 1, 2, 3 \ldots \)

Shubnikov-De Haas oscillations

Resistance standard
25812.807557(18) \( \Omega \)
Light emitting diodes

- Absorption
- Reflection
- Total internal reflection

[Diagram of light emitting diode with labels for emitted photons, absorbed photons, GaAsP, GaAs, graded alloy GaAs$_{1-y}$P$_y$ (y = 0 → 0.4), and reflective contact.]
Bandgaps
Double Heterojunction lasers

http://spie.org/x18854.xml