# CLUSTER ION BEAM FACILITIES

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A brief state-of-the-art review in the field of cluster-surface interactions is presented. Ionised cluster beams could become a powerful and versatile tool for the modification and processing of surfaces as an alternative to ion implantation and ion assisted deposition. The main effects of cluster-surface collisions and possible applications of cluster ion beams are discussed. The outlooks of the Cluster Implantation and Deposition Apparatus (CIDA) being developed in Göteborg University are shown.

## Introduction

In the last few years there has been a growing interest in using cluster beams. It is motivated by demands to synthesis novel materials and to renovate the existing technological operations where ion beams have almost reached their intrinsic limits [1] and some goals are difficult to achieve by using accelerated ions [2]. Ionised cluster beams become a powerful and versatile tool for the modification of materials and processing of surfaces as an alternative to ion techniques. With clusters consisting of up to few thousands atoms it is possible to transport a large amount of material. Compared to ions, clusters generate multicollision effects with low energies at high densities that minimises radiation damage and channelling. By cluster assembling it is possible to produce a material with novel properties and to control surface parameters. The properties of clusters depend on the number of constituent atoms or molecules. By controlling the size and structure of a cluster one can change electronic, optical and chemical parameters of the agglomerate. Many groups have studied the properties of free clusters in molecular beams and reviews of results were presented [3, 4]. Investigations on atom-cluster and cluster-cluster collisions have been done as well [5-7]. However the interaction of clusters implanted in a substrate are poorly studied so far. There are a lot of fundamental physical aspects that have to be investigated to provide successful production of materials with the required parameters using cluster assembling. On the other hand it is universally recognised that an ideal approach or setup to produce intensive cluster beams with well controlled parameters does not exist. Hence, there is a broad action field in the technical sphere of a cluster beam formation and adjustment.

## I. Cluster-surface interaction: main effects

One of the main advantages of an ionised cluster is low charge to mass ratio. To accelerate the agglomerate consisting of hundreds of atoms one can ionise only one of them. An acceleration of, for example, 100 atoms cluster with 10 keV causes on average 100 eV acceleration of each constituent atom. Non-linear collisions occurring during the impact of accelerated cluster ions upon substrate surface produce fundamentally low energy bombarding effects at very high density. A number of bombarding characteristics can be emphasised for practical applications. Cluster ion beams are well suited for thin film deposition, shallow implantation, dry etching, surface cleaning and smoothing (see Fig. 1) [8]. Effects of high-density energy deposition allow the formation of thin films and the growth special reliefs. Clusters accelerated with higher energy can be used for modification of shallow substrate layers. High efficiency of sputtering yield and lateral sputtering effects of cluster-surface collisions give the possibility of changing surface morphology and formation of specific structures. Cluster beams provide high directionality useful for anisotropic etching.

The first use of accelerated ionised clusters to synthesise thin films and heterostructures has been proposed by Takagi and Yamada [9]. Nowadays a number of scientific groups deal with cluster implantation and deposition.

## II. Low energy deposition

Direct ion deposition and ion-assisted processes are candidates for thin film formation. But energy bellow 100 eV is very difficult to obtain with ion beams. Cluster beam deposition (CBD) can be considered as a more promising technique that allows control the kinetic energy and mass of the particles in the ranges which are unattainable for ions. For example, one can decrease the deposition energy per atom bellow the cohesion energy and deposit the cluster on the surface without destroying the cluster structure. Experiments with antimony and gold clusters deposited on graphite confirmed the absence of fragmentation at very low energies [10, 11]. It is possible to vary the degree of coalescence and particle-surface adhesion by controlling the incident energy and fluence of clusters. Sticking coefficient and adatom mobility on the substrate surface influence the nucleation and growth of the particle agglomerates. The existence of a critical size for cluster coalescence was found [12]. The colliding clusters with sizes smaller than the critical one have a tendency to form larger particles. If the cluster size is above a critical value, islands consisting of clusters without coalescence will appear. The ramification of islands and their aggregation were observed depending on the increasing beam fluence.

The very important role played by defects in coalescence process on surface was shown [13, 14]. The growth of nanostructures by landing of clusters can be stabilised by controlling the density of defects created by those clusters on the surface. The kinetic energy of 1 eV/atom was established as the limit over which the damaging effects became sizeable. The growth of films via low-energy cluster beam deposition can be viewed as a random stacking of particles. The characteristic length scales are determined by cluster dimensions and their behaviour

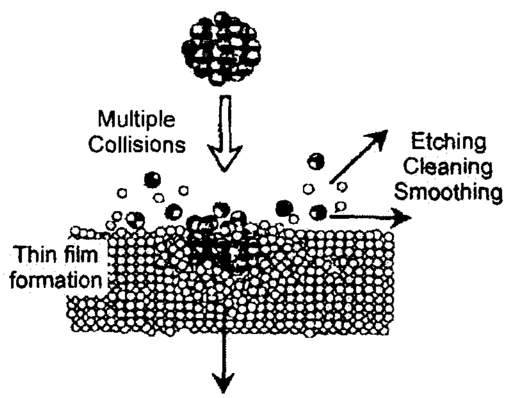


Fig. 1. Possible applications of cluster-surface effects

during deposition. Besides characteristics of the cluster (mass, structure, energy, fluence et al), there are a lot of parameters such as sticking coefficient, nucleation density, adatom mobility, substrate temperature, surface defects etc. influencing film growth or formation of different structures by clusters.

For the last few years experiments on film growth using cluster beams were done. CBD of semiconductor-based nanostructured materials is a subject of considerable interest due to the advanced optical and electronic properties. For instance, nanostructured silicon films obtained by CBD with controlled particle size show higher photoluminescence intensity than porous silicon [11]. Thin carbon films with structure from amorphous carbon to graphite-like materials were obtained by size selection of clusters in the beam [15]. The formation of the materials characterised by single-size metal particles or assemblies of particles with well-defined size distribution is a very promising direction for applications in non-linear optics and as high-density memory devices [16, 17]. The method for growth of Ag microstructures (bars) on a substrate by using a grid mask with high deposition rate of the cluster beam was developed [18]. The possibility to vary the shape of the deposited structures by using a combination of masks was demonstrated by Barborini at al [19] using carbon cluster beams. Deposited on the surface metal clusters themselves can be used as nuclei for mask creation. Such technology was used for Si pillars formation by subsequent plasma etching of the masked surface [20]. The silicon structures with accurately controlled pillar diameters can be used as colour screens.

Cluster beams offer also such advantage as homogeneous dispersion of embedded clusters [11] which is promising for production of composite materials. A wide variety of cluster-matrix combinations can be chosen for composites production. One of the interesting applications is synthesis of crystalline polyimide films [21] that is characterised by good control of the imidization process and crystallographic properties due to the high surface-migration energy, surface-cleaning effect and creation of activated centres for nucleation of the polymer layers.

## III. High-energy effects: implantation, sputtering, etching

Shallow junction formation in Si is one of the most topical applications of cluster beam implantation. Nowadays technology has led to the use of lower and lower energy and has moved to heavier implant species: from P to As and Sb for n-type and from B to $BF_2$ for p-type semiconductors because novel generation of MOSFETs already needs to have junctions of 30-80 nm. According to predictions, in ten years 10 nm junctions will be in use. But for p-type Si this result can not be obtained with ion implantation due to boron enhanced diffusion. Clusters of $B_{10}H_{14}$ were used for shallow junction formation and recently a 7 nm ultra shallow junction was formed [8]. As result the smallest transistor with 40 nm effective gate length was produced.

It was suggested by simulations and confirmed by experiments that impact of clusters with surface is substantially different from ions. Particularly, very high sputtering yields on any surfaces (metal, semiconductor and insulator) due to large cluster bombardment were observed [8]. Experiments on angular distribution of material sputtered by diverse cluster ions at different incidence angles and energies have allowed to optimise technology for surface smoothing, cleaning and etching. Main advantages of cluster use in comparison with ion or plasma assisted processing are high spatial resolution, short-range damage and elimination of charge accumulation on a substrate surface. A better smoothing effect was achieved at low deviation from normal to surface angles of incidence. Increasing of incidence angle of cluster beam from normal direction to surface leads to enhanced lateral sputtering effects of material [22]. This is a new non-equilibrium mechanism of surface modification, which does not depend on heating or melting of material.

Dissociation of clusters due to the high-energy impact can promote chemical reactions on the substrate surface leading to the formation of volatile species and assisting the physical erosion of the target. The etching of Si and $SiO_2$ by $SF_6$ cluster ions was demonstrated [23]. Very high sputtering yield allowed the processing of patterns that is difficult to prepare with traditional plasma etching. Pyrex glass microstructuring by $CO_2$ clusters shown high efficiency in formation of regular repeated structures using mask on the beam way to the target [24].

## IV. Outlook of CIDA

At the present stage the new ultra high vacuum (up to $10^{-10}$ Torr) apparatus CIDA has been designed and constructed. A schematic diagram of the apparatus illustrating the different in situ and ex situ analysis techniques that are already present (LEED/Auger spectrometer, optical analyser on the basis of ICCD camera with spectrograph, MCP ion detector) or in the planning stage (time-of-flight mass spectrometers, electron detectors) is given in Fig. 2. There is the possibility to use a range of in situ laser diagnostic techniques (e.g. second harmonic generation on the target surface etc.).

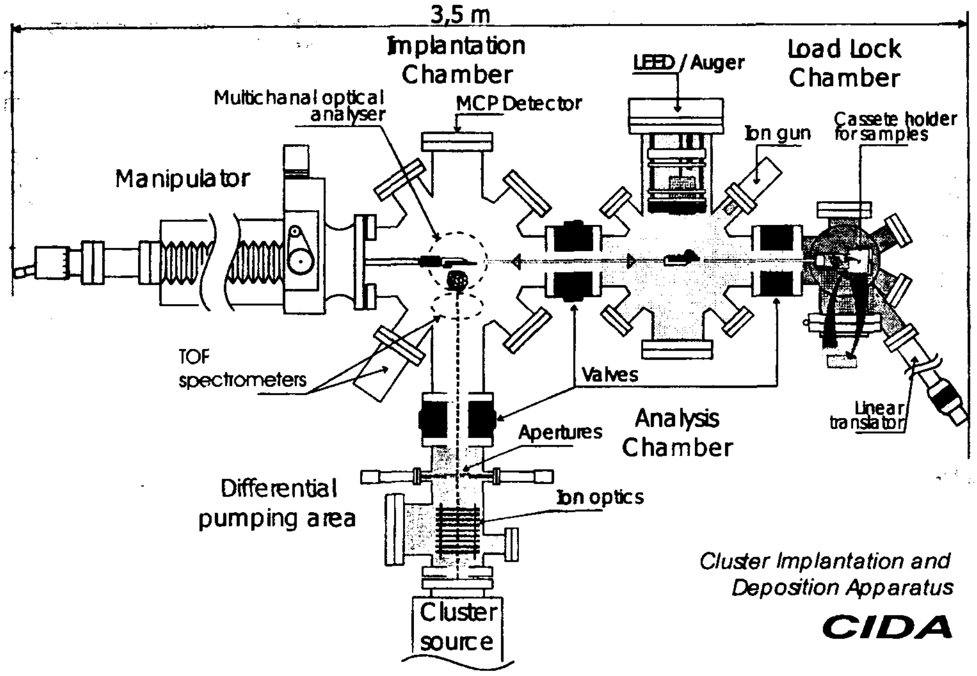


Fig. 2. Schematic diagram of the CIDA

The pulsed nozzle cluster source for gas phase precursors is currently being tested for Ar and $N_2$ clusters. The nozzle has the considerable advantage of producing very short pulses compared to other commercial systems thus reducing the pumping requirements and allowing UHV conditions to be easily reached. It also works at very high stagnation pressure (up to 100 bar) which is advantageous for producing large clusters.

Cluster ions, predominantly from gas-phase precursors, will be used to implant semiconducting and dielectric materials. It is planing also to explore the potential of large clusters of fullerenes $(C_{60})_N$ produced by a vaporisation source [25] for making thin diamond-like films. These films could also be doped in a controlled fashion by other clusters. Systematic studies of cluster size and impact energy dependence on the defect production, optical and electronic properties of the implanted targets will be carried out as well. Both in situ and ex situ analysis methods will be employed to study the principal physico-chemical mechanisms involved in the cluster ion – target interaction.

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