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(54) Title: METHOD AND APPARATUS FOR SURFACE TREATMENT BY COMBINED PARTICLE IRRADIATION

(57) Abstract: The invention relates to a method for surface treatment of a substrate surface by irradiation of particles onto the substrate constituting the substrate surface. The method comprises the steps of applying first particles onto the substrate surface, thereby causing a positive particle flux component on the substrate surface and emitting eroding particles as at least an eroding particle beam onto the substrate surface, the eroding particle beam causing a negative particle flux component on the substrate surface. The application is performed concurrently or alternately with the step of emitting. An area of the substrate surface onto which the first particles are applied is at least partly overlapping an area of the substrate surface irradiated by the eroding particle beam in an overlapping area of the substrate surface. The resulting cumulative flux of the combined positive and negative flux components in the overlapping area being non-positive, the resulting cumulative flux providing a decreasing or stable net amount of particles in the overlapping area of the substrate surface. The first particles and the eroding particle beam comprising atomic or molecular particles, wherein the first particles are provided by a source outside a plane coextending with at least a part of the substrate surface. Further, the invention relates to a device for surface treatment and a target device for carrying out the inventive surface treatment method.

5 # Method and apparatus for surface treatment by combined particle irradiation

Technical Field

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The present invention relates to surface treatment by a particle beam combined with the deposition of auxiliary particles. In particular, the present invention relates to surface treatment for smoothening, roughening or eroding a surface according to desired surface properties.

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Background of the Invention

Substrates of metals or semiconductors can be treated by radiation of charged or uncharged
20 particles in order to change the surface properties. Ion guns are used for generating an ion beam, i.e. positively or negatively charged atoms, which are accelerated by an electric field. The kinetic energy of the ions impinging onto a surface of a substrate is transformed into changes in the lattice structure of the selected irradiated substrate at the surface and at an area adjacent to the surface. Depending on the energy of the ion beam, the fluence (i.e.
25 number of particles on an area), the flux (i.e. number of particles propagating through or transmitted onto an area per second), the inclination between beam and surface, the chemical element or compound constituting the substrate and the element(s) of the ion beam, particles of the substrate located at the substrate surface are removed and/or stimulated. The removal of particles from the surface of a solid is denoted as erosion. The
30 erosion yield can be determined by using an momentum based model of the lattice addressing the bonding energy and the interaction between ions and atoms constituting the solid. The terms "flux" and "fluence" denote properties of the propagation of particles and relate to the number of particles passing or arriving at an area, e.g. a cm^2. "Flux" is the derivation the "fluence" per time; fluence is the sum, i.e. the integral of the flux over time.
35 Features referring to flux properties are related to equivalent features referring to fluence properties and vice versa by referring the above mentioned relationship. Thus, all features

referring to "flux" also define equivalent features referring to "fluence" and vice versa by applying one of the equations: (1) $flux = \partial fluence(t) / \partial t$; (2) $fluence = \int flux(t)\, dt + c$, $c = const.$, $c \in \Re$. These definitions of "flux" and "fluence" relate to statements concerning the state of the art as well as features and statements set out in the description of the present invention and the claims appended thereto.

For the deposition of material onto a substrate surface it is known to use sputter sources or plasma sources which provide uncharged and charged particles, respectively, the particles being in the size of atoms, small molecules or atom clusters. The well known technique of sputtering is realized by a sputter target, which is irradiated with accelerated ions emitted by an ion beam source, for example an ion gun. The ions impinge onto the sputter target and, upon interaction with the surface of the sputter target, atoms or other particles of the sputter target are released into the space adjacent to the sputter target. In this way, the sputter target is eroded, and the released atoms (or ions) deposit onto a substrate surface located nearby the sputter target. In this way, the particles (i.e. atoms or atom clusters or ions) deposit on the substrate surface with a low thermal energy.

As another technique for applying particles onto a surface, a part of the material can be converted into plasma (i.e. stimulated atoms or ions), resulting in the deposition of stimulated particles on a substrate surface. Further, material (for example metal), can be vaporized and recondensed, i.e. deposited onto a substrate surface located nearby.

Further techniques for surface treatments are known, which combine the above mentioned erosion/deposition processes. In ion beam assisted deposition (IBAD), ion implantation is combined with simultaneous sputtering or physical vapor deposition. Thus, during deposition of particles (i.e. atoms or ions or clusters thereof) the substrate surface is stimulated by the ion beam energy in order to control the properties of the layer, which is being deposited on the surface. Since IBAD is a deposition techniques for constructively forming layers on a substrate, it can not be used for eroding a given substrate surface. Further, the emitted ion beam is suited for implanting ions in a certain depth of the substrate and, consequently, adds material to the substrate.

In US 2002/003086 A, another combination of sputtering and ion beam irradiation is described, in which a deposition source (sputter source) deposits atoms and molecules on a substrate. After sputtering, the same substrate is irradiated with an ion source for improving the uniformity of the deposited layer. Thus, the ion source does not erode or deposit a material on the surface. The application US 2003/0111336 A1 discloses the fabrication of silicon cones on a silicon substrate by irradiating a silicon target. At the circumference of the target, a catalyst material is arranged as a flat foil mounted around the

target. The target as well as the catalyst material extend in a common plane. An ion source irradiates the target and the catalyst material thereby forming cones in the silicon surface. The only shape that can be provided with the described arrangement are arrays of small cones etched into the silicon; no other geometrical surface properties can be achieved. Further, US 2003/124717 A describes to implant metal ions into a substrate and to deposit material by CVD (chemical vapour deposition). The metal ions implanted in the substrate lead to cylindrical structures during the CVD-process. However, no treatments for providing surface properties apart from cylinders are described. Further, the treatment described therein is based on deposition of material and does not disclose to treat the surface by erosion without the application of additional material onto the substrate.

A vapour deposition system with multiple sources is described in the application US 2004/0139914 A1 providing an evaporation process with mixed materials. This application is directed to specific mixtures of materials, which are deposited onto the substrate, and is not applicable for the treatment of a given surface without application of material, for example by treatment for eroding a substrate surface. US 2005/087268 A describes another combined assembly for application of material onto a substrate. It is described to use one common ion source for sputtering both, a copper target and a tungsten carbide target in order to deposit a layer of a combination of both materials. In the same way, US 2006/114616 A describes a method for generating a thin film on a substrate, comprising a first ion beam to generate sputtered particles, in combination with another ion beam to form a granula film with particular magnetic properties. Similar to the methods described above, the method of this publication addresses the deposition of material rather than surface treatment without the application of additional material, for example a treatments implying erosion. Another deposition technique is shown in US 2006/177581 A for providing coatings by assisted physical vapour deposition. An electron beam source for vaporizing metal is combined with an ion beam source for assisted deposition of the vaporized metal. US 2006/177581 does not describe any treatments for eroding a substrate surface or for processing a surface without the application of material.

Patent US 5,473,165 describes the treatment by means of a mixed proton and carbon beam for heating or eroding a surface substrate. The combined ion beam is used for applying energy to the surface rather than applying particles or removing particles from the surface. The apparatus shown in US 5,473,165 can be operated only in one mode and is not adapted for combined treatments, i.e. deposition combined with erosion of material.

Another device for sputter deposition is shown in US 5,667,650 B, which is adapted for applying a layer onto a substrate surface. This application neither shows surface treatment without the deposition of extrinsic material nor discloses a combination of erosion and

deposition. US 5,916,423 B describes sputter deposition and ion milling however for applying an additional layer on a substrate and without addressing surface treatments without applying extrinsic material. In the same way, US 6,043,960 B shows a deposition method comprising the deposition of an intrinsic layer, which is ion milled for treating the extrinsic layer. Further, US 6,150,558 B relates to the treatment of a deposited layer and does not disclose the treatment without depositing persistent extrinsic material. Also US 6,224,719 B shows the treatment of an deposited layer rather than disclosing methods for eroding a surface without applying persistent material. The same relates to the treatments described in US 6,274,007 B; US 6,460,243 B; US 6,468,405 B or other publications for creating a layer of extrinsic material, which is subsequently treated, for example by patterning.

In „Atom assisted sputtering yield amplification" by S. Berg, A. Barklund, B. Gelin, C. Nender, I. Katardjiev, J. Vac. Sci. Technol. A 10 (1992), pp. 1592 et. seq., sputter simulations concerning sputter yield enhancements are described for sputtering of Si and C with 1 keV Ar ions under simultaneous co-deposition of a certain amount of Pt. The study relates to the deposition by sputtering; no eroding surface treatment mechanisms are described.

Other publications, for example "Ripple Formation and magnetic Texturing of paramagnetic Thin Films by Sputter Erosion", K. Zhang et al., New Journal of Physics, 9/2007, show the formation of ripple patterns by sputter erosion using an ion beam inclined to the substrate surface irradiated thereby in an angle of more than 70°. Other publications relate to the deposition of extrinsic material on a surface using assisted deposition, however, without addressing treatments which do not include the application of extrinsic material. Such deposition treatments are described in "Characterisation of Gradient Interfaces in Thin Film Multilayers Used to Protect Orthopaedic Implants", R. Hübler, Surface and Coatings Technology, 116-119 (1999) pages 1116-1122; "Effects of the TI/AL Atomic Ratio of the Properties of Gradient (Ti, Al) and Films synthesized by Ion Beam assisted Deposition", Xiao-Ming He, et al., Journal of Vacuum Science and Technology, pages 845-850, "Preferential Sputtering Effects in Thin Film Processing" S. Berg et al., Journal of Vacuum Science and Technology, 1999, pages 1916-1925; "Fabrication and Microstructures of SI Composite Nano Con Erase" X. M. Meng, Phys. Stat. Sol., Nr. 13, pages 2479-2783 (2005) and „Resputtering Effects during Ion Beam Assisted Deposition and Sputter Yield Amplification Effect", Sörenberg et al., Surface and Coating Technology 84 (1996), pages 353-362.

Summarized, combined particle sources like ion guns and sputter sources are used for deposition techniques, wherein one source deposits atoms onto a surface and another

source manipulates the deposition process (for example by heating). Further, erosion processes are known e.g. ion etching or plasma etching, both of which providing certain surface properties, for example roughness or ripple forming, which cannot be arbitrarily selected. In particular, the surface properties strongly depend on the used materials and the arrangement of ion source and substrate surface. As an example, US 2003/0111336 A1 shows a surface treatment, which is exclusively adapted for forming cone arrays; no other forms or surface properties (smoothness) can be yielded with the treatment described therein. Thus, the prior art surface treatment processes are very specific to the material and to the desired surface properties and do not provide any flexibility. In particular, no surface treatment based on particle sources is known which allows to arbitrarily adjust surface smoothness, ripple forming, erosion as well as deposition yield in a simple and precise manner.

Summary of the Invention

According to the invention, the application of particles is combined with the emission of eroding particles onto the same area (i.e. an overlapping area). The area irradiated by both particle sources, for example a substrate surface, is subjected to the opposed effects of both sources. The two sources together provide an eroding, roughening or smoothening effect, essentially without depositing a persistent layer onto the substrate surface. Thus, the source emitting the eroding particles and the source applying particles (denoted as first particles) onto the substrate together provide a non-positive flux of particles onto the substrate surface. In other words, the emission of eroding particles overrules or at least compensates the application of the first particles onto the substrate surface, wherein the application of first particles onto the substrate leads to a modulating temporal thin coating which strongly influences the effect of the eroding particles. The first particles applied onto the substrate do not remain on the substrate surface in great number but form "surfactant" atoms with a strong impact on the interaction between the eroding particles impinging onto the substrate surface and the atoms of the substrate surface.

In order to modify the impact of the applied particles (first particles or surfactant atoms), the source of the first particles is arranged outside the substrate surface and outside the plane in which the substrate surface extends. In this way, the position of the source of the first particles relative to the substrate surface can be adjusted according to the yielded effect. In other words, the positive particle flux of the first particles applied onto the substrate surface can be set and modified by adjusting the position of the source providing the first particles. In contrast to a particle source coplanar with the substrate surface which implies a non-linear and indirect path of the particles propagating from the particle source towards the substrate surface, the present invention allows a direct transfer from source to

substrate and a linear propagation path. The application of particles onto the substrate surface in a direct and linear way allows a precise control of the particle flux onto the substrate surface. Further, the flux can be easily adjusted by setting an inclination between source and substrate surface, by setting the position of the particle source relative to the substrate surface, or by a combination thereof. For particular settings and materials, specific surface effects occur (forming of ripples, forming of con arrays), which can be easily inhibited, provoked or adjusted by setting the position of the source applying first particles with regard to the substrate surface.

In this document, the term particles describes atoms, molecules or atom clusters, molecules, molecule clusters, ions or ion clusters, charged molecules or charged molecule clusters in the atomic scale, i.e. with only one, two or few atoms or molecules. Typically, particles as used herein are products of an ion source like an ion beam, a sputter target irradiated by an ion beam, an evaporating source like a vapor oven in vacuum or a plasma source. The first particles, i.e. the particles applied onto the substrate surface operating as "surfactant" atoms are preferably uncharged particles with a low kinetic energy. Disregarding the effect of the eroding particles, the kinetic energy of the first particles, i.e. the surfactant particles or surfactant atoms, allows a net deposition of the particles onto the substrate such that the amount of particles remaining on the substrate surface is higher than the amount of particles rebounding from the substrate surface (disregarding the effect of the eroding particles). The density of the first particles or surfactant particles remaining on the substrate is preferably relatively low, for example with a density less than 5×10^{16} particles/cm^2, including the influence of the eroding particles which remove surfactant particles from the surface.

According to the invention, the eroding particles are the product of an ion gun, a particle accelerator or another source for uncharged or preferably charged particles with a high kinetic energy. The eroding particles are irradiated onto the substrate surface in an eroding particle beam, preferably having a cross section with a constant flux over the cross section area. Advantageously, the eroding particle beam is collimated and has a cross section which is constant and along the propagation direction of the eroding particle beam. Preferably, ions or charged molecules or other charged particles are used, since the particles of the eroding particle beam can be provided with a high kinetic energy by applying an electric or electrostatic field along the desired acceleration direction. Further, cathodic arc devices can be used if it is provided that the particles emitted by the cathodic arc device has a high kinetic energy suitable for removing particles from the substrate surface. The eroding particles impinge onto the substrate surface and interact with particles in the surface, being preferably bound by a lattice in order to remove particles from the surface and from the lattice. In other words, the kinetic energy is higher than the bond

energy in the lattice of the substrate surface. Thus, the eroding particles remove material from the substrate surface.

The effect of the particles, i.e. the deposition characteristics of the first particles (surfactants) and the erosion effect of the eroding particles are determined by the kind of particle material, the kinetic energy, kinetic energy distribution, fluence, flux, particle mass and inclination between propagation direction of the respective particle and the irradiated substrate surface. In particular, the chemical elements or molecule of the material providing the respective particles have an impact on the effects of the beam. For example, inert gas atoms of one element or of plurality of elements are used as eroding particles and elements like gold, silver or copper are preferably used for the surfactant particles or first particles.

The source for applying the first particles, i.e. the source for the surfactant atoms or first particles, which are deposited unto the substrate surface, can be an active source or a passive source. If the source providing the first particles is an active source, the first particles are provided by a source and are accelerated by the source, e.g. by heating or accelerating charged particles. If the source for the first particles is provided as passive source, the source only provides the material, i.e. the molecules, atoms or clusters thereof providing the first particles, which are accelerated by the impulse (impact) of a high energy beam, e.g. an ion beam. An example for a passive source is a sputter target, which is irradiated by a high energy ion beam, the ion beam interacting with atoms at the surface of the sputter target. In this way, the sputter target releases some atoms from its surface, the released atoms forming a "cloud" of released atoms with a relatively low energy. Since the atoms released from the sputter target have a relatively low energy, they are deposited on a substrate surface located adjacent to the sputter target. In this way, the sputter target transforms the high energy of an ion beam irradiating a sputter target into a low kinetic energy of the released or sputtered atoms of the sputter target. The released atoms (or particles like atom clusters or molecules) are deposited onto an adjacent substrate surface.

The ion beam irradiating the sputter target can additionally be used as source for eroding particles, i.e. the ions forming the ion beam. Thus, a part of the ion beam (or a part of the cross section of the ion beam) is directly directed onto the substrate surface, thereby eroding the substrate surface, and an other part of the ion beam (another part of the cross section of the ion beam) sputters atoms from a sputter target, thereby providing surfactant particles or first particles, which are applied to the substrate surface. In this way, a part of the ion beam, together with the sputter target, forms an active source of first particles or surfactant particles, whereas the sputter target itself forms a passive source for first particles. Since the ion beam directly or indirectly provides both, the first particles as

applied onto the substrate surface as well as the eroding particles, the ion beam source is a dual function particle beam source, providing a dual function particle beam. Further, both parts of the ion beam have the same propagation direction. The sputter target preferably fulfils two conditions: (1) the sputter target is aligned with the ion beam to receive the ions and (2) the sputter target is inclined inwardly towards the substrate surface in order to provide sputtered atoms onto the substrate surface in a direct way. The propagation direction of the ion beam is preferably perpendicular to the substrate surface and inclined with the sputter target surface in an angle between 0° and 90°. The propagation direction of the ion beam preferably forms an acute angle with the sputter target surface. In this way, the sputter target emits sputtered atoms onto the substrate surface in an effective manner. In other words, an angle near to 90° between sputter target surface and substrate surface provides a good transfer of sputtered atoms (i.e. atoms eroded from the sputter target) onto the substrate surface.

The first particles can be applied simultaneously with the emission of eroding particles onto the substrate surface or the first particles are applied in alternation with the emission of eroding particles onto the substrate surface. If the step of applying is performed alternately with the step of emitting the eroding particles, a shutter can be used which obstructs the eroding particles when the first particles are transmitted onto the substrate surface and which obstructs the propagation of the first particles towards the substrate surface while passing the eroding particles to the substrate surface. If a dual function ion beam and a sputter target is used for providing both, the first particles as well as the eroding particles, the shutter for periodically enabling/blocking the flux or propagation of the first particles can be arranged between the ion source and the sputter target or between the sputter target and the substrate surface.

Basically, the materials used for the first particles SURF (i.e. the surfactant material), the eroding particle beam, a beam sputtering a sputter target (if applicable) as well as the material providing the substrate and the substrate surface have a fundamental impact on the efficiency and kind of effect of the method for surface treatment according to the invention. Regarding the material SUB providing the substrate in the substrate surface and the applied first particles SURF (the surfactant), the following three alternatives are given: (1) the material of the substrate SUB is identical with the surfactant SURF, (2) the surfactant material SURF is soluble in the substrate material SUB and (3) the surfactant material SURF is insoluble in the substrate material SUB. In the case of identical materials and soluble materials, the surfactant is added to the lattice of the structure, forms an alloy or is bound to the substrate in another stable way, preferably providing a relatively high binding energy.

According to a first example, the surfactant material comprises or is provided by an element, which is lighter than the substrate material. In some embodiments according the first example, sputter yield amplification can be provided for particular operational parameter settings. In a second example, the surfactant material comprises or is provided by an element, which is heavier than the substrate material.

According to a particularly preferred embodiment, soluble (i.e. miscible) material systems (solid solutions) are distinguished from insoluble (non-miscible) material systems by their phase diagram (phase boundaries as function of composition and temperature) determined by the minimum of Gibb's free enthalpy $G = H - T \cdot S$. The temperature T of interest is the substrate temperature during treatment. As an example, a miscible system of distinct material has its lowest Gibb's enthalpy for the solid solution. Consequently, the Gibb's free enthalphy of a non-miscible system of substrate material and a surfactant is lowest for phase separated substrate material and surfactant. In some cases partially miscible systems may form a compound with defined stoichiometry and a pure phase of the remaining excess material. Examples for partially miscible systems are M (metals), in particular Pd, Cu or Pt surfactants on a Si substrate form M_xSi silicides and M (metal) precipitates. Such partially miscible systems are miscible systems according to the invention.

According to a preferred embodiment, miscible systems are distinguished from non-miscible systems by means of the spatial material distribution. For miscible systems, homogeneous distributions of the distinct materials can be achieved. However, for non-miscible systems, the materials are spatially separated, e.g. by a layer or a volume substantially consisting of surfactant material arranged on or in a substrate section substantially consisting of substrate material. In this context, "essentially consisting" means: comprising more the 90%, 95 %, 98 %, 99%, 99,5% by weight of the respective material.

According to another embodiment of the invention, soluble (i.e. miscible) material systems are distinguished from insoluble (non-miscible) material systems by the binding energy between the distinct materials. As an example, the binding energy in an miscible system of substrate material and a surfactant miscible therein is higher than an energy binding limit of 0.5 eV, 0.2 eV or 0.1 eV. Consequently, the binding energy in an non-miscible system of substrate material and a surfactant non-miscible therein is lower than such an energy binding limit.

Combinations of materials miscible in a substrate for providing an alloy or a chemical compound are for example: Au surfactant on a Si substrate, Pt surfactant on an Fe substrate, Si-surfactant, Al-surfactant or both on an SiO_2 -substrate. The substrate can be

completely formed of the substrate material or can provide a surface layer formed of the substrate material. At the substrate surface, the surfactant and the substrate material preferably form a thin layer of mixed materials (e.g. an alloy). Further, depending on the substrate material and the surfactant material miscible therein, substrate material and surfactant can provide a composite, a nano-composite, a cluster or a combination thereof. The surfactant SURF dissolved in the substrate material SUB preferably forms a binary system with one common phase comprising both, the substrate material as well the surfactant material miscible therein. In one embodiment, the binary system of surfactant/substrate comprises an eutectic point or area, preferably for conditions which are met when carrying out the invention. An example of surfactant/substrate mixtures providing an eutectic point or an eutectic area is Au-surfactant on an Si-layer. Preferably, the surfactant SURF (when applied on the substrate SUB) forms a substrate section comprising a homogeneous mixture of both, the surfactant material and the surface material. Further, the surfactant or a part thereof, combined with the substrate surface, can provide a compound. According to the invention, a surfactant material forming a compound with the substrate material can be denoted as being soluble in the sense of the invention. Such compounds can have other properties than the surfactant material and the substrate material. Thus, such compounds can form a continuous layer, nano-composites or clusters. For example, if Fe-surfactant is used on a C-substrate, carbides are formed on the substrate surface. Depending on the structure and material distribution of the SURF/SUB-mixture, smoothing, ripple forming, roughening and other topographical properties of the substrate surface can be provided. The effect is strongly related to the used materials, the kind of mixture (continuous layer/clusters), and angle of incidence of the eroding particles. For example a system comprising Au-surfactant on a Si-substrate forms an alloy layer in an eutecticum when carrying out the invention. Preferably, the mixtures and alloys formed of the substrate material and the surfactant material have a melting point below the melting point of both, the substrate material and the surfactant material.

Instead a surfactant material provided by one chemical element or compound, a combination of more than one surfactant elements SURF, compounds or alloys can provide the surfactant material. In the same way, the substrate material SUB can be a combination or a mixture of more than one material. If surfactant materials soluble in the substrate are used, the smoothness of the substrate irradiated with eroding particles is increased. Surfactant materials SURF soluble in the material of the substrate SUB are equivalent to materials miscible in the substrate material, preferably providing a homogeneous mixture with at least a part of the substrate surface material (e.g. the part constituting a substrate section of the substrate). Preferably, the surfactant material or the substrate material or both are metals, semiconductors, alloys, or alloys of metals and semiconductors.

Surfactant materials, which are not soluble in the material of the substrate or substrate surface, are bound to a substrate lattice or substrate structure with a low binding energy. In particular, insoluble surfactant materials do not form an alloy or a chemical binding with the material of the substrate and do not form a layer of (homogenously) mixed materials. Rather, surfactant materials, which are not soluble in the surface material, remain on the substrate surface as a separate layer. In the case of non-miscible systems, the surfactant may form a continuous surface layer (example: Cu surfactant on Fe substrate) or may disintegrate into islands or clusters at the surface (example: Ag surfactant on Si). Preferably, for surfactant materials non-miscible in substrate materials, a spatial separation and therefore a minimum interface area between both materials is favourable as regards the energy. Thus, the reduction of interface area between both materials is an inherent effect of the material system leading to a segregation or demixing of the mixture in the long run. These effects can provide a strongly inhomogeneous distribution of surfactant material on the substrate. Thus, "islands" can be provided protecting the underlying substrate at one area, wherein an adjacent area is subjected to erosion leading to a strongly inhomogeneous distribution of the obtained erosion depths. A system of non-miscible SUB/SURF materials (in contrast to miscible systems) could be defined by a low binding energy (e.g. < 0.5 eV, < 0.2 eV, < 0.1 eV) or by the spatial distribution of the materials as discussed above with regard to miscible systems. If the surfactant material is not soluble in the substrate material, the emission of eroding particles onto the substrate generally increases the roughness, in particular, if the eroding particles are emitted onto the substrate in an angle of < 90° between particle beam and substrate surface, e.g. in an acute angle of incidence. A preferred system is Ag surfactant on a Si substrate.

The opposite effects of soluble surfactant materials and insoluble surfactant materials can be explained by the mixture of soluble surfactant materials and substrate material, forming a compound or an alloy with a lower melting temperature, in particular, if the mixture is provided in an eutectic area or point. In this way, the surfactant materials enhance the effects of the eroding particles and lower the binding energy of the substrate surface material with the underlying substrate. In contrast thereto, materials, which are not miscible in the substrate material form an "extrinsic" layer or cover particles lying on the substrate surface. The cover particles are loosely bond to the substrate surface and comprise a very high concentration of surfactant material (are loosely bond to the substrate surface and comprise a very high concentration of surfactant material (> 95%, > 98 % or > 99%) since the substrate material is not soluble or miscible in the surfactant material. In this way, the system provided by surfactant material and substrate material at the substrate surface form a system with two distinct phases. Thus, small cover particles are formed protecting the underlying substrate from erosion. Depending on the coverage and the inclination of the eroding particle beam, the erosion process provides a rough surface. In

particular for a relatively low coverage, the surfactant material forms clusters, the clusters discontinuously covering the substrate surface. Thus, the effect of the eroding particle beam is strongly decreased at positions covered by a surfactant cluster, and provides a high erosion yield at uncovered positions, leading to a strongly increased roughness. A high roughness might be preferred for surfaces onto which electrodes are applied or or other structures of semiconductor devices. In particular, the invention allows to provide surfaces with individual or extreme surface properties as regards friction, adhesion and wetting. Depending on the dimensions, particular optical properties can be modified or provided. Further, if the surfactant material is identical with the substrate material, the surfactant particles applied onto the substrate form a lattice different to the lattice provided by the underlying substrate, such that the surface properties and the effect of the eroding particles are modified.

Preferably, the eroding particles are inert ions, in particular Ar or Xe ions, or are N_2 or O_2 ions, or a combination thereof. Additionally or in combination therewith, Cs ions, Ga ions or a combination thereof can be used, in particular for providing a high roughness or particular ripple patterns or enhanced ionised sputter particle emission from the substrate (which is important for SIMS). Depending on the substrate material, some of the ions can be inserted into the substrate surface (i.e. into the lattice) during the eroding process without further impact on the properties of the substrate surface.

For surfactant materials insoluble in the substrate materials, Cu, Ag, Au, Co, Pb and Pt can be used for carbon substrates; Ag, Zn, Sn, Sb, Pv, Pt can be used for silicon substrates; Al, Sn, Sb, Ag, Bi, Pt can be used for germanium substrates or substrates comprising germanium like GaAs; Mg, Cu and Pb can be used for iron substrates; Fe, Pb or Bi can be used for copper substrates and Ag or Pt can be used for SiO_2 or Al_2O_3 substrates. Of course, the substrates can be completely formed of the respective substrate substance or can comprise a layer which is formed of the respective substrate substance. Further, the surfactant materials can be atoms formed of one of the above mentioned elements, or can be a compound or a mixture of the above-mentioned surfactant elements.

For surfactant materials identical to the substrate surface any element, alloy or compound can be used. As an example Si, Ag or Au provide the surfactant material SURF as well as the substrate material SUB. Further, any of the above mentioned chemical elements forming a solid under treatment conditions can be used.

The present invention can be used to form thin ferromagnetic alloys. Upon treating a substrate, e.g. a substrate covered by a thin layer, according to the invention, ferromagnetic thin layers formed in an upper section of a substrate layer covering a (non-magnetic)

substrate can be formed. As an example, the substrate can be provided with a thin upper substrate layer of Fe, which is treated according to the invention using Pt as surfactant. After completion of the treatment, an Fe-Pt alloy remains on the substrate. The Fe-Pt alloy is ferromagnetic and has a thickness of preferably less than 2 nm, less than 1 nm, less than 5 nm or less than 2 nm. Other combinations of substrate materials/surfactant materials can be used, e.g. Co-Nb, Co-Sm or Ni-Fe, wherein the first element denotes the substrate material (or surfactant material) and the second element denotes the surfactant material (or the substrate material). Preferably, the substrate material is formed as a thin layer covering a non-magnetic substrate as support, e.g. Si or SiO_2. Generally, all ferri- or ferromagnetic elements, compounds or alloys can be used, in particular lanthanide compounds or alloys.

The present invention can be used to treat a layer of SiO_2 on Si. According to one embodiment, a thin layer of SiO_2 is formed on Si by annealing in air, i.e. by thermally oxidizing a Si substrate. Al or Si is used as surfactant in combination with a Xe ion beam @ 5 keV, $3 \cdot 10^{16}$ particles/cm² or $7.6 \cdot 10^{16}$ particles/cm² as eroding particles at an acute angle of incidence, e.g. 70° or 80°. The Al or Si co-sputtering target (as a source of surfactant or first particles) is inclined to the ion beam at an angle of 30° or 15°. In addition or as an alternative, a substrate with an upper layer of SiO_2 (e.g. a substrate according to the preceding example) can be patterned using a cover layer of photoresist, which is illuminated acording to a desired pattern, e.g. trapezoid areas and developed to remove the illuminated areas. The areas remaining on the substrate (i.e. the areas which have not been illuminated) form a cover on the substrate surface and prevent erosion at areas covered with resist, in contrast to unprotected areas, which are subjected to erosion and surface treatment according to the invention. In one embodiment, the photoresist forms a stripe mask with 1mm period. A waveguide can be formed using two patterned substrates, the treated substrate surfaces of which face each other. The substrates are bonded together, e.g. by Au-Si alloys on a substrate surface (e.g. formed of Si). In this way, the substrate bulk forms an outer reflection layer (or layer with higher refraction index) surrounding the eroded SiO_2 substrate surfaces. Since the surfactant is applied onto the substrate surface with a varying thickness or fluence along the surface (e.g. with a constant gradient), the erosion leads to a thickness gradient in the substrate or an upper layer of the substrate. In the example above, conical waveguides with a SiO_2 core (or with a Si core, if an upper section or the substrate is formed of Si) can be provided, e.g. for visible or UV light or for X-ray radiation. Other optical applications of the invention comprise the treatment of a $LiNbO_3$ substrate or of a substrate comprising a top layer of $LiNbO_3$. In particular, substrates formed of a first material and covered with a top layer of a second material, the first and the second material having distinct optical properties, can be treated according to the invention. In this context, optical properties comprise: refraction index, attenuation, birefringence and anisotropic properties.

In general, the effects of the eroding particles can be modified by the density, by the kind of the surfactant material as well as by combination thereof. In order to provide a gradient for the effect of the eroding particles, i.e. the eroding yield or sputter yield, the density of the surfactant material on the substrate surface can be varied along the surface, e.g. by varying the distance between the respective point on the substrate surface and the source of the surfactant material. Varying the density of the surfactant material on the substrate surface is equivalent to the variation of the concentration or of the coverage provided by the surfactant material, which can be measured in percent or in particles or atoms per cm^2.

According to one aspect of the invention, the source of the surfactant material is a layer irradiated with ions, i.e. a sputter target surface. E.g. in case of a homogeneous cross section of the ion beam emitted onto the target surface, a sub straight surface inclined to the target surface is provided with a high density or coverage of surfactant atoms at a position near to the target surface and receives only a low concentration or coverage of surfactant atoms in a position far away from the surfactant source, i.e. far away from the target surface. In this way, the eroding effects are modified by applying surfactant atoms in a concentration varying with the position. Depending on the surfactant material, i.e. material soluble or insoluble in the material providing the substrate surface, a position or an area close to the target surface is heavily eroded or is "protected" by a high concentration of surfactant material.

Alternatively or in combination therewith, the kind of surfactant atoms provided by a surfactant source can be varied depending on the position on the sputter target surface. Thus, a combined target can be used with an area of soluble surfactant atoms and an area of insoluble surfactant atoms. Further, a gradient can be provided, ranging from a high concentration of soluble atoms at one position of the target surface ranging to a high concentration of insoluble surfactant atoms at another position of the target surface.

Additionally or in combination therewith, a gas flow can be used to provide a gradient or gradient component regarding the density of the surfactant atoms by transporting at least a part of the surfactant atoms from one position to another, preferably before the surfactant atoms are applied onto the substrate surface. According to one embodiment, a gas stream is directed onto the target surface. In another embodiment, the density of the surfactant atoms is modified by a curved target surface, a curved substrate surface or a combination thereof, which provides gradients different to nearly linear progressions. However, in a preferred simple embodiment, the substrate surface as well as the target surface are planar, abut to each other, the target surface being inclined to the substrate surface. In this embodiment, the eroding particle beam perpendicularly impinges onto the substrate surface and in an

inclined angle onto the target surface according to the inclination between target surface and substrate surface.

According to another aspect of the invention, an ion source provides an ion beam, a part of
5 which provides the source for the eroding particles, and another part of which is directed onto a target surface inclined to the ion beam as well as to the substrate surface for providing surfactants material, that is first particles, which are applied to the substrate surface. Alternatively or in combination therewith, the source for the surfactants material, i.e. the source for the first particles to be applied onto the substrate, is an active source,
10 independent from the source emitting the eroding particles. In both cases, an IBAD (ion beam assisted deposition) arrangement could be used, which is operated below the resputter limit. In other words, the effects of the eroding particles (the ion beam) onto the substrate surface is stronger than the effects of the first particles applied to the substrate surface, such that in total, no material is applied onto the substrate surface. In other words,
15 an IBAD assembly could be used which is operated below the resputter limit, without forming a layer onto the surface. Rather, the IBAD system is operated for eroding or smoothening a given substrate surface. Again, the IBAD arrangement is operated such that no net film deposition occurs, no layer is grown onto the substrate (apart from the relatively low concentration of surfactant particles, which are temporarily applied onto the
20 substrate surface).

From a certain point of view, the present invention is complementary to ion beam assisted deposition (IBAD). The main feature of IBAD is to apply material onto a surface by sputtering. In order to modify the deposition properties, an ion beam irradiates ions onto
25 the deposited material for modifying the deposition process. Like, IBAD, the invention can be implemented by an ion beam source and a sputter source, however with inversed functions. According to the invention, the ion beam is used for eroding a surface as main feature of the process. A particle source (e.g. a sputter source) modulates the eroding process by applying particles. Thus, according to the invention, the particle source
30 modifies the main process of eroding (performed by an ion beam). This can be seen as a reverse approach in comparison to IBAD, since in IBAD an eroding process (provided by the ion beam) is modified by the (temporary) deposition of material, e.g. provided by a sputter source

35 According to one aspect of the invention, a source providing surfactant material is combined with the source for eroding particles, the eroding particles dominating the surfactant particles as regards the surface treatment. Irrespective if a conventional IBAD arrangement is used, or not, one aspect of the invention provides a method for dosing the radiation of both sources, the method providing a relationship between the fluences of both

sources, such that only few surfactant particles are applied onto a substrate surface and are provided in a steady state of particles under the influence of the eroding particles irradiating onto the substrate surface and therewith irradiating onto the surfactant particles. The emission of the sources is controlled according to a mean coverage provided by the fluence or flux of the surfactant particles in relation to the effective fluence or flux of the eroding particles, which is preferably averaged over a certain time period. The resulting relative mean coverage f, which is the coverage averaged over time, can be homogeneously distributed over the complete substrate surface (i.e. $f = \text{constant}$) or can be varying according to gradients or distributions in order to yield the desired varying erosion effect. The relative mean coverage is a relative measure and refers to 10^{15} atoms/cm^2 (typically) as absolute reference. As an example, a relative mean coverage f of 0.5 corresponds to an absolute value of $f \cdot 10^{15}$ atoms/cm^2 = $5 \cdot 10^{14}$ atoms/cm^2. According to a first model used for providing doses for the sources carrying out the method according to the invention, $f = \ln (1 / (1 - J_d / (J_e \cdot Y_s)))$, with: J_d being a flux of first particles provided by the first particle source to the overlapping area; J_e being a flux of eroding particles provided by the eroding particle beam source to the overlapping area; and Y_s being the sputter yield associated with the eroding particles. In a second, less exact model, $f = J_d / (J_e \cdot Y_s)$. The second model is preferably used for settings in which $J_d \ll (J_e \cdot Y_s)$. The second model can be derived from the first model by known approximation methods, e.g. Tailor series expansion up to the first n terms, $n = 1, 2, 3, 4$ or < 8. The relative mean coverage f preferably lies within at least one of the following intervals: [0.0001; 10], [0.001; 4], [0.001; 1], [0.001; 1], [0.01; 0.5] and is preferably greater than 0.00001 and less than 10 or lower than 5 or lower than 2. In another model, $f = 1$ is equivalent to a (theoretical) continuous coverage of the substrate surface by the surfactant particles with a thickness of one particle (atom).

According to the invention, $J_d / (J_e \cdot Y_s)$ is < 1, < 0.5, < 0.1 or < 0.01, depending on the desired erosion effect. For $J_d / (J_e \cdot Y_s)$ close to 1, the erosion effect is low; for $J_d / (J_e \cdot Y_s)$ substantially equal to 1, there is no erosion and no deposition (i.e. surface treatment without reduction of substrate thickness, equivalent to a combined positive and negative flux components in the overlapping area of substantially zero). For $J_d / (J_e \cdot Y_s) \ll 1$, the erosion effects are dominating leading to a fast reduction of substrate thickness.

Preferably, the coverage provided by the surfactant particles is less than $5 \cdot 10^{16}$ particles/cm^2, less than $5 \cdot 10^{15}$ particles/cm^2 or less than $1 \cdot 10^{15}$ particles/cm^2 and more than $1 \cdot 10^{12}$ particles/cm^2 or more than $1 \cdot 10^{13}$ particles /cm^2.

In another embodiment, a distribution of the desired erosion depth is given for various positions on the substrate. A corresponding distribution of coverage by the surfactant

particles is derived using a direct dependency between coverage provided by the surfactant atoms or particles and the erosion efficiency. Starting from the derived coverage density, the shape or, correspondingly, the position of points constituting the sputter target on the substrate surface can be determined by considering each point of the sputter target as a point source of particle irradiation according to Huygen's law and integrating the impact of each point on a respective position. Alternatively, the shape of the sputter target can be transformed into the respective radiation characteristic by applying a corresponding mapping function on to the shape of the sputter target as positioned in space and aligned with the substrate surface.

Each of these dependencies can be linearly approximated or can be given as an (in)complete series expansion. Further, other approximation equations can be used or look-up tables can be provided in an empirical way, which form the basis for the respective dependency or form the basis of an interpolation providing the dependency. In particular, the dependency between coverage, sputter yield and erosion effect can be provided by experimental data, physical considerations regarding the stochastical, structural momentum related and binding energy related properties of the respective particles and surfaces. Further, this is discussed in the description of the Figures and the Figures itself.

The method for surface treatment as well as the method for dosing the radiation of a surfactant source (i.e. a first particle source) and an eroding particle beam source (e.g. an ion beam) can be implemented by software running on a processor. According to the instructions provided by the software, control signals are generated by a processor, e.g. in combination with an I/O interface, which is connected or which is adapted for being connected with a respective apparatus comprising at least one of each of the sources. Further, the processor can be connected with an user interface, allowing the user to input the desired erosion depth distribution. Preferably, the user input interface is combined with a graphical user interface which provides feedback showing the user inputs as a graphical reproduction, the resulting fluence density distribution reached after a certain time duration or related to a steady state, the resulting flux density distribution (instantaneous value or mean value averaged over a shifting time window) or a combination thereof.

Advantageously, the substrate surface, the sputter target, another surfactant atom source or a combination thereof is provided with a mask applied on the respective surface. The mask is preferably formed of a resist layer, e.g. a photoresist layer, which partly covers the surface, and which partly does not cover the surface. The mask is an additional measure for structuring the substrate surface by partly blocking the eroding particles as well as the surfactant particles. In particular, the mask can form one or more gaps tapering towards one end, e.g. in a linear way, the tapering direction being parallel or being in a plane

perpendicular to a sputter target. Preferably, the tapering direction lies in a plane in which the substrate surface extends. In this way, waveguides can be formed, e.g. for X-ray radiation, which are in the form of a trapeze and which are provided with a layer overlying the substrate, the layer having a thickness gradient with a constant increasing or decreasing rate along the direction in which the wave guide extends. The form of the trapeze provided in one plane can be structured using a mask, e.g. a photolithographic mask, while the thickness gradient can be provided by a respective distribution of surfactants particles on the surface substrate, which is preferably the result of a sputter target inclined to the surface substrate and abutting to one edge of the surface substrate.

In general, substrates can be treated, which are homogeneous, or which are covered by a layer. If covered by a layer, the layer of the substrate is considered as a part of the substrate and is being treated according to the invention.

In additional studies, it has been found that the surfactant material does not act as catalyst modifying the surface treatment. Rather, it has been found that the surfactant material is part of the substrate surface. Depending on the materials, the surfactant material and material of the substrate surface form an alloy, the alloy having a continuous concentration gradient extending perpendicular to the substrate surface and comprising a layer of nearly pure surfactant material, a layer of an alloy of surfactant material and substrate material, and a layer of (nearly) pure substrate material. In other material combinations, an inhomogeneous mixture is formed of particles, clusters, of continuous layers of surfactant material covering a (nearly) pure layer of substrate material. These structures are provided as a final result of the inventive surface treatment.

Some studies have suggested a buried layer of surfactant material within the substrate surface, the buried layer being covered by a continuous or discontinuous layer of substrate material. In other words, some results have suggested a buried layer sandwiched between a thin layer of substrate material and the substrate itself. In “Nanostructured carbide surfaces prepared by surfactant sputtering”, by the inventor, H. Hofsäss, K. Zhang and H. Zutz, Universität Göttingen, Germany, held at IBMM-2008, Dresden, Germany, September 1-5, 2008, studies have been presented according to which the measured effective carbon sputter yield as function of surfactant area density has been determined for W and Ti surfactants, respectively. In the case of W surfactants, the sputter yield has been considered as rather independent of the W coverage varying between 10^{16} and $3\cdot 10^{16}$ W/cm^2 and about 50% reduced compared to the pure ta-C surface. SRIM simulations assuming a thin W layer on ta-C but also TRIDYN simulations taking into account ballistic mixing of W and C due to collision cascade effects have been considered not to explain the magnitude and coverage dependence of the measured sputter yield. Even the calculated sputter yield

assuming a WC layer on ta-C was somewhat lower than the experimental values. As a conclusion, the W+C layer visible in TEM can be described as amorphous W_xC with x smaller but close to 1. The formation of a nearly stoichiometric WC steady-state surface layer requires ion induced diffusion processes in addition to ballistic mixing. Strong ion-induced diffusion was recently also observed during Si erosion using Au surfactants, leading to a buried Au_xSi surfactant layer. In general, ion-induced diffusion is been considered as one mechanism resulting in buried layers.

The studies have been published in: „Surfactant Sputtering“ Appl Phys A, by the inventor, Hans Hofsäss and Kun Zhang, published online on May 28, 2008 which is incorporated herein in its entirety. According to these studies, sputter erosion examples were carried out at room temperature using a 5 keV mass selected Xe-ion beam, ion fluences up to 1.2 10^{17} cm^{-2} and an incident angle α of 70° or 80°. The pressure during erosion was 2 10^{-6} Pa. The ion flux was about 2 $\mu A/cm^2$, so that heating of the samples by the ion beam is negligible. The ion beam was provided by a Colutron Model G2 mass selective ion beam system using a plasma ion source and a Wien-filter for mass selection. The beam with diameter of few mm and beam divergence of less than 1° was swept across the sample area using an electrostatic beam sweep system. The typical samples size was 10 7 mm^2 and the homogeneous ion beam cross section was about 1.2 cm^2. As samples we used silicon, silicon with polymer resist surface patterns, thermally grown silicon dioxide on Si, and metal films (Fe, Ni) evaporated on silicon or glass substrates. The substrates and the films, prior and after sputter erosion, were analyzed by atomic force microscopy and scanning electron microscopy. Rutherford backscattering spectroscopy (RBS) using a 900 keV He^{2+} beam was applied to determine the initial and final film thickness, the experimental sputtering yield and the sputter depth. The sputter depth of some samples was also analyzed using a profilometer.

An illustrative example of these studies has been carried out as follows. During sputtering of initially 140 nm thick Fe thin films on glass using 5 keV Xe ions at α = 80°, the films were exposed to a flux of Cu atoms, originating from a Cu sputter target with surface normal parallel to the ion beam (β = 0°). Angle α is the angle of incidence of the sputtering ion beam impinging onto the sputter target, angle β is the angle of incidence of the ion beam impinging onto the substrate surface. After sputter erosion, a fluence dependent thickness gradient was measured using cross sectional SEM. For sputtering of pure Fe a sputter yield of $Y_{bulk, Fe} \approx 15.3$ atoms/ ion and a corresponding sputter depth of about 220 nm at fluence 1.2 10^{17} ion/cm^2 has been expected. Instead, the effective sputter yield varies between 12 and 3 atoms/ion across the sample. The Cu–Fe system is immiscible and it is expected that surfactant sputtering with Cu leads to a steady state Cu surface coverage which reduces the Fe sputtering yield. AFM analyses of ripple patterns measured after

erosion at different sample positions did not show Cu cluster formation. This indicates a rather homogeneous steady state surface coverage. At the end of the ion irradiation, the surface coverage in dynamic equilibrium is frozen in and remains as an ultra-thin surface layer. RBS analyses reveal a layer thickness varying from 0.05 nm and 0.4 nm across the samples, independent of the ion fluence. This independence is expected for a steady-state surface coverage. Furthermore, the example demonstrates that surfactant sputtering may also be used to generate surfaces covered with ultra-thin films.

A model reflecting the physical laws underlying these studies has shown results similar to the behaviour observed in the illustrative example mentioned above. In this illustrative example we obtain a variation of the effective Fe sputter yield between 12 and 3 atoms/ion, corresponding to a ratio $0.19 \leq a/b \leq 0.77$ as calculated according to the model. The ratio a/b is equal to $j_D/(j_I \quad Y_{S,bulk})$, j_D being the deposition flux of surfactant atoms and j_I $Y_{S,bulk}$ being the maximum surfactant erosion ion flux, wherein j_I is the ion flux and $Y_{S,bulk}$ is the sputter yield for the surfactant material (i.e. the sputter target). The result for the ratio a/b corresponds to a saturation area density of Cu varying between $2.6 \quad 10^{14}$ and $1.8 \; 10^{15}$ cm^{-2}, or a Cu layer thickness between 0.03 and 0.2 nm. The somewhat higher value determined from Rutherford backscattering spectroscopy measurements is possibly due to a small amount of dispersed Cu atoms recoil implanted in to the subsurface region of the Fe film.

In “Fundamentals of surfactant sputtering” by Hans Hofsäss and Kun Zhang, Georg-August University Göttingen, Germany, held on ICACS-23, Phalaborwa, South Africa, August 17-22, 2008 “surfactant sputtering” further results related to the inventive surface treatment have been disclosed. As a result, the inventive surface treatment is a novel technique for surface modification utilizing a steady-state surface coverage with surfactant atoms simultaneously during ion beam erosion. A simple bi-layer model system consisting of a uniform surfactant layer and the underlying substrate allows one to establish basic rate equations for the surfactant coverage describing the growth regime with a linear increase of coverage with time but also the sputtering regime generating a steady-state coverage of the substrate with surfactant atoms. For sputtering of Fe films with Cu surfactants the steady state Cu coverage has been demonstrated. TRIDYN simulations are used to model the sputter yield attenuation as function of surfactant coverage. For Fe sputtering with Cu surfactants a thin CuFe layer due to ballistic mixing is formed. In the case of sputtering of Si with Au surfactants the results strongly support a dynamic equilibrium characterized by strong interdiffusion of Si and Au, resulting in a buried Au_xSi layer covered by a thin Si layer. The inventive method for surfactant sputtering is a useful technique to prepare novel nano-scale surface patterns, to smoothen surfaces, to prepare thickness gradient films or to grow ultra-thin films as frozen-in dynamic equilibrium.

Description of the Drawings

Fig. 1a shows a device implementing the concept of the invention with a passive source providing surfactant particles;

Fig. 1b shows a device implementing the concept of the invention with an active source providing surface particles;

Fig. 2 (a)-(i) show measured sputter effects for various configurations;

Figs. 3 and 4 show sputter yield simulation results for a gold substrate covered with silicon at different projection angles;

Fig. 5 shows sputter yield simulation results for a silver substrate with covered with silicon;

Figs. 6, 7, 8 and 9 show preferred embodiments for carrying out the invention.

Detailed description of the Drawings

Fig. 1a as well as Fig. 1b show a device comprising a source for eroding particles S1 emitting a collimated beam of ions in the direction shown with arrows 1 and 1'. The device shown in Fig. 1a comprises a sputter target S3, which is irradiated by the ion beam, in particular by a part of the ion beam 1. The sputter target surface S3 emits first particles 3, i.e. surfactant atoms upon irradiation by the part of the ion beam 1 impinging onto the sputter target S3. The atoms or particles (e.g. atom clusters) sputtered off or released from the sputter target surface S3 are emitted in various directions, and in particular in the direction shown with arrow 3 towards a substrate. Since another part of 1' of the ion beam emitted by the ion beam source S1 is directed onto the substrate 2, the substrate 2 and therewith the substrate surface also receives eroding particles, i.e. ions directly from the ion source 1. The eroding particles emitted by the ion source have a relatively high energy leading to a negative particle fluence component or, in other words, to the release or removal of particles, i.e. atoms from the substrate surface 2.

Thus, substrate surface 2 is simultaneously treated by a part 1' of the ion beam (causing erosion), as well as by the first particles or surfactant atoms 3 released from the sputter target S3 (which causes a positive particle fluence component or the (temporal) position of atoms). Therefore, the source of the first particles S3 is a passive source which only provides the particles and receives energy from the particle beam 1 for releasing or sputtering off the surfactant atoms.

In contrast thereto, ion source S1 of Fig. 1b exclusively provides the eroding particles (i.e. the ions) and does not generate surfactant particles (i.e. first particles). An active source S3 completely independent from S1 provides surfactant particles. In Fig. 1b, the flux of particles is shown as a beam denoted with arrow 3; however, depending on the kind of source S3, the first particles are not emitted in a collimated beam but form a "cloud" of particles i.e. surfactant atoms emitting from a surface of the surfactant source S3. E.g., S3 can be an oven vaporising atoms provided by a solid film or can be an individual sputter source, the sputter source comprising an individual ion beam source irradiating a sputter target, the sputter target and in particular the sputter target surface delivering the first particles.

As can be seen from Fig. 1b, the area irradiated by the first particle source S3 is not necessarily identical with the area radiated by the eroding particle beam 1. Similarly, the arrangement shown in Fig. 1a does not provide identical irradiation areas. However, both arrangements provide an area in which both irradiation areas at least partly overlap. From Fig. 1a, it can be easily seen that the inclination of the substrate surface 2 relative to the sputter surface provides a surfactant atom concentration decreasing with the distance to the irradiated sputter target S3. Similarly, the surfactant particle source S3 can be arranged to emit surfactant particles in an inhomogeneous flux distribution.

In Fig. 2, nine diagrams (2(a) - 2(i)) related to the measured sputtering effect are shown. Sputtering is provided by an ion beam 1, for example a Xe ion beam with an energy of 5 keV, which irradiates a substrate surface 2, in this case a silicon substrate. At the y-axis, the sputter effect of each of the nine arrangements is depicted, wherein 0 relates to an erosion depth of zero (no erosion), and –140 relates to the removal of a surface layer with a thickness of 140 nm by erosion. Together with the results (shown as marks connected by lines), in each of the sections (a–i), the spatial relationship or alignment between ion beam, silicon substrate and a sputter target 3 is shown. In particular, the inclination between sputter target surface and substrate surface (both extending in plane) is shown, together with the respective angle a (reference sign 4). The position denoted on the x-axis (Figs. 2(b) – 2(i)) refers to the position of measurement on the substrate from left to right (in Fig.2(a) from bottom to top)

The arrangement shown in section (a) does not comprise a sputter target wherein each of the arrangements shown in sections (b) – (i) comprises a sputter target 3, which is perpendicularly irradiated by the ion beam 1. Further, the arrangements shown in Figs. 2(b) – (i) comprise an angle a denoting the inclination between the propagation direction of the ion beam 1 and the silicon substrate 2. It is to be noted that in other parts of the description and the claims, an other orientation defining the angle are used. According to the other orientation, an angle α is defined by the inclination of a substrate surface and the sputter target (perpendicular to the ion beam). Thus, angle a used in Fig. 2 differs from the angle α as used in other parts of the description and the claims. In other words, angle a is complementary to angle α.

Fig. 2(a) shows a standard erosion process different to the invention, in which the substrate 2 is irradiated only by an ion beam with an inclination of 90°.

In Figs. 2(b) - 2(i), an ion beam 1 perpendicularly irradiates a sputter target 3 (and not the substrate surface 2) and, additionally, irradiates the substrate surface in an acute angle. Starting from a relatively open angle of a = 45° between substrate surface 2 and propagation direction of the ion beam 1, Figs. 2(b) - 2(i) show arrangements with an angle a decreasing until a small angle of a = 6° in Fig. 2(e) is reached. It can be seen that the erosion effects in Figs. 2(a) and 2(b) are relatively constant, and that with decreasing angle a, the relationship between sputter effect and surfactant coverage varies.

On the x-axis of each section of Fig. 2, the distance along the substrate surface is given, starting from the edge of the silicon substrate 2 opposing the sputter target 3 towards the edge of the substrate abutting the sputter target. Since at positions near to the sputter target (position 6 mm, 5 mm, 4 mm) the source of surfactant atoms (i.e. the sputter target 3) is close to the substrate and a high concentration of surfactant atoms on the substrate surface is produced at these positions. The concentration of surfactant atoms decreases with increasing distance between the actual position on the substrate and substrate edge located close to the sputter target. It can be seen that at positions close to the sputter target (e.g. 6 mm, 5 mm), the eroding effect is relatively low and increases with increasing distance from the sputter target, i.e. increases with decreasing surfactant atom concentration. E.g. by comparing Fig. 2(c) with Fig. 2(g), it can be seen that inclination angle a has a significant impact on the course of the sputter effect depending on the position and shows that an inclination of 10° provokes a very high variation of sputter effect along the distance from the sputter target. Further, it can be seen that the dependency is not necessarily linear (like in Figs. 2(c), 2(g)) and can show dynamic developments, e.g. Fig. 2(d). These dependencies are based on two effects: (1) with increasing angle a, the coupling between

ion beam particles 1 and substrate surface 2 increases, and (2) with increasing angle a, the emission of surfactant atoms from the sputter target onto the substrate decreases. Further, the shape of the sputter target and in particular the inclination between sputter target and substrate defines (varies) the surfactant concentration gradient along the substrate surface.

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In Figs. 3 – 5, results of the simulation of bilayer systems with a thin upper layer are depicted. The simulation comprises the irradiation of the upper layer with an ion beam of Xe at an energy of 5 keV. The sputter yield is given for the upper layer as well as for the lower layer in atoms/ion, i.e. removed atoms of the respective surface per ion irradiated
10 onto the surface. In Figs. 3 – 5, the sputter yield related to the lower layer (equivalent to the substrate surface) is depicted in curves with circular marks. The sputter yield related to the upper layer (equivalent to the first particles or surfactant atoms) is shown with square marks. Since the invention is focused on eroding a substrate (and not a thin upper layer), the dependency between substrate sputter yield (= lower layer sputter yield) and thickness
15 of the upper layer (the surfactant atoms) should be focused on.

In Figs. 3 and 4, the material of the upper layer, i.e. the first particles, is solvent in the material of the lower layer (the substrate). In Fig. 5, the material of the upper layer is insoluble in the material of the lower layer.

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In Figs. 3 and 4, the effects of silicon surfactant atoms on a gold substrate (Au) are depicted, whereas Fig. 5 shows the effects of silicon surfactant atoms on a silver substrate (Ag).

25 In Fig. 3, the ion beam impinges perpendicularly onto the substrate surface. For a film thickness provided by the surfactant Si atoms between 0 and 0.3nm, the sputter yield strongly depends on the surfactant film thickness showing a linear dependency. Such simulated dependencies between coverage provided by the surfactant atoms and the sputter yield can be combined with measurements or can replace measurements in order to
30 determine an adequate coverage for a certain desired sputter yield.

Additionally, the simulation of Fig. 3 shows that for a perpendicular incident ion beam onto the surface the sputter yield of the surfactant atoms (silicon) significantly increases above the bulk value, i.e. the sputter yield for homogeneous block of silicon (=Si_{bulk}). This
35 effect is known as sputter yield amplification.

Fig. 4 shows a simulation similar to the simulation shown in Fig. 3, apart from the incident angle of the ion beam onto the substrate surface. In Fig. 4, the ion beam impinges onto the substrate surface in an acute angle of 10° between propagation direction between ions and

substrate surface. Fig. 4 shows similar dependencies between sputter yield and surfactant atom coverage, however, with a generally reduced sputter yield. Additionally, the simulation of Fig. 4 shows that the acute angle between ion beam and surface only slightly increases the sputter yield of the surfactant atoms (silicon) above the bulk value, i.e. the sputter yield for homogeneous block of silicon (=Si_{bulk}). Thus a sputter yield amplification effect is almost absent under acute angle irradiation.

In contrast to the soluble systems of Figs. 3 and 4, in which silicon covers gold, Fig. 5 relates to a system of silicon surfactant atoms, covering a silver substrate Ag. The ions impinge perpendicularly onto the substrate. It can be seen that for small coverages, i.e. a film thickness of surfactant atoms between 0 and 3 nm, a linear dependency between sputter yield and film thickness is given.

Further simulations have shown that for insoluble systems an ion beam irradiation in an acute angle onto the substrate surface covered with surfactant atoms provokes significantly increased ripple forming corresponding to an increased roughness. Further, it could be shown that the ripple frequency, i.e. the distance between two adjacent ripples can be modified by modifying the angle of incidence of the ion beam (= eroding particle beam) onto the substrate. In particular, for small angles between ion beam and substrate surface, a strong dependency between surfactant atom coverage and roughness could be measured for foreign atoms (material of the surfactant particles different to the material of the substrate). E.g. in an angle of 20° between substrate surface and ion beam, the ripple forming can be nearly completely suppressed by using surface particles miscible in the substrate surface and can be significantly increased using surfactant particles or materials, which are not miscible in the surface material. Further, the wave length of ripples can be varied according to the coverage of surfactant particles miscible in the substrate, and in particular by using surfactant atoms which are not miscible in the substrate.

In Fig. 6, a preferred embodiment for carrying out the invention is given. A broad and homogeneous ion beam 10 is incident on a substrate 20, which is to be treated. The substrate 20 can be tilted in an angle 21 from 0° to almost 90° with respect to the beam direction. Further, the embodiment comprises a mechanism (not shown), which is adapted for moving the substrate 20 perpendicular to the beam 20, preferably periodically, for a homogeneous treatment. Only a part of the ion beam 10 irradiates a substrate surface 20. Other parts of the ion beam irradiates one or more sputter targets 31, 33. Preferably, the targets are attached to a rotation device (not shown) for rotating the targets in the directions shown with reference signs 32 and 34. In the embodiment shown in Fig. 6, the sputter targets 31 and 33 are arranged with respect to the ion beam 10, the ion beam source (not shown) and the substrate 20 such that atoms sputtered off the target or targets 31, 33 are

deposited on the substrate 20. In this way, a laterally inhomogeneous coverage with sputtered atoms is produced. Together with the effects provoked by the ion beam 10, thickness gradients can be produced when eroding or treating the substrate 20. One of the sputter targets 32 or 32 of both sputter targets can be fixedly positioned as an alternative.

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In Fig. 7, another embodiment for carrying out the invention is shown, in which a broad an homogeneous ion beam 10 is incident on a substrate 20, which is to be treated. The embodiment shown in Fig. 7 further comprises a mechanism (not shown), which tilts the substrate in an angle from 0° to almost 90° with respect to the beam direction. Further, a
10 mechanism (not shown) can be provided in order to rotate the substrate 20 as shown with arrows 22. If the substrate is supported in this way, the method for surface treatment can be performed in an homogeneous way. A second ion beam 40 irradiates a sputter target 30, which can be tilted in an angle 31 and rotated as shown with arrows 32. Alternatively, the target can be fixedly positioned, can only be tilted or can only be rotated. In order to rotate
15 the sputter target 20, another rotation mechanism is provided (not shown). The target 30 is aligned with respect to the second ion beam and the substrate 20 such that the atoms sputtered off the target are deposited onto the substrate 20 thereby producing a laterally homogeneous coverage with sputtered atoms. Preferably, the surface of the sputter target is arranged substantially in parallel to the substrate surface 20. The embodiment shown in
20 Fig. 7 can be used for smoothening the surface of the substrate 20.

In Fig. 8, a third preferred embodiment for carrying out the invention is shown. A broad and homogeneous ion beam 10 is incident on a substrate 20, which is to be treated. The substrate can be tilted in an angle 21 from 0° to almost 90° with respect to the beam
25 direction. Preferably, the embodiment shown in Fig. 8 further comprises a moving mechanism attachable to the substrate, the mechanism being adapted to move the substrate in a direction 22 vertically to the beam direction 10 for homogeneous treatment of the substrate. As in Fig. 7, the embodiment shown in Fig. 8 comprises a second ion beam source producing a second ion beam 40, which irradiates a sputter target 30. The sputter
30 target 30 can be tilted in an angle 31, can be rotated as depicted with arrows 32, or both. The target 30 is positioned with respect to the substrate 20 and the ion beam 40 or the ion beam source (not shown) such that the atoms sputtered off the target are deposited on the substrate 20, producing a laterally homogeneous coverage with atoms sputtered off the sputter target 30. Preferably, the surface of the sputter target 30 irradiated by the second
35 ion beam 40 is substantially parallel to the substrate surface 20 or is inclined to the substrate surface with a small angle, preferably less than 30°, 20°, 10°, 5° or 3°. (This also applies to the sputter target and the substrate surface of the arrangement of Fig. 7). Additionally, the arrangement of Fig. 8 comprises movable shutters 11 and 33 between the first sputter beam source 10 and the substrate 20 and/or between the sputter target 30 and

the substrate 20, respectively. The shutters are preferably attached to moving mechanisms, which are synchronised in order to alternatingly shut off the ion beam and the flux of first particles from the sputter target to the substrate surface. In other words, the movable shutters are rotated in order to alternatingly enable the application of first particles and the emission of eroding particles onto the substrate surface. In this way, the contamination of the sputter target can be reduced, since a reduced number of ions constituting the first ion beam 10 is added to the substrate 20.

Fig. 9 shows a fourth embodiment for carrying out the invention comprising an ion source (not shown) providing a broad and homogeneous ion beam 10 incident on a conical substrate holder 20 carrying a number of substrates 22, 23, 24, which are to be treated. Preferably, the embodiment shown in Fig. 9 comprises a mechanism for rotating the substrate holder around its symmetry axis 21. The ion beam 10 is further directed onto a sputter target 30, which is preferably attached to another rotation device. Substrate holder 20 and target 30 are positioned coaxial with the symmetry axis perpendicular to the ion beam. The conical angle of the target 30 and the substrate 20 are arranged to provide a flux of surfactant particles sputtered off the target, the flux being directed onto the substrate holder 20 (the substrates 22, 23, 24), thereby producing an radial inhomogeneous coverage with surfactant atoms.

Preferably, ion beam sources providing eroding particles are used, which emit a broad ion beam with a large cross section and a homogeneous fluence across the cross section. Alternatively, an ion beam can be used for providing a beam with a small diameter, the ion beam source further comprising a sweeping device for sweeping the beam across a certain area in order to broaden the effective beam cross section. Preferably, an electrostatic beam sweep system is used.

In general, the arrangements shown in Figs. 6 – 9 can also be used for IBAD, i.e. for depositing a layer by sputtering, wherein the deposition process is supported by an ion beam (emitting eroding particles) irradiating the area on which the layer is deposited. For using the devices shown in Figs. 6 – 9 as deposition devices, the deposition effect provided by sputtering is stronger than the eroding effect provided by the ion beam source.

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Patent Claims

1. A method for surface treatment of a substrate surface by irradiation of particles onto the substrate constituting the substrate surface, the method comprising the steps of:
5 applying first particles (3) onto the substrate surface (2), thereby causing a positive particle flux component on the substrate surface (2);
emitting eroding particles as at least an eroding particle beam (1') onto the substrate surface (2), the eroding particle beam (1') causing a negative particle flux component on the substrate surface (2), wherein
10 the step of applying is performed concurrently or alternately with the step of emitting;
an area of the substrate surface (2) onto which the first particles (3) are applied is at least partly overlapping an area of the substrate surface (2) irradiated by the eroding particle beam (1') in an overlapping area of the substrate surface, the resulting
15 cumulative flux of the combined positive and negative flux components in the overlapping area being non-positive, the resulting cumulative flux providing a decreasing or stable net amount of particles in the overlapping area of the substrate surface;
the first particles (3) and the eroding particle (1') beam comprising atomic or
20 molecular particles, wherein the first particles are provided by a source (S3) outside a plane coextending with at least a part of the substrate surface.

2. The method according to claim 1, wherein
the first particles (3) comprise atoms, atom clusters, molecules, molecule clusters,
25 ions, plasma, or a combination thereof, and
the eroding particles comprise accelerated ions, plasma, charged particles, or a combination thereof, and wherein
the first particles are applied under operational parameters providing the positive particle flux component, the operational parameters comprising at least one of:
30 fluence, chemical compound of the particles, chemical element of the particles, kinetic energy distribution or mean kinetic energy of particles, particle mass and inclination of a source delivering the first particles relative to the overlapping area, and
the eroding particle beam (1') is emitted under operational parameters providing the
35 negative particle flux component, the operational parameters comprising at least one of: fluence, chemical compound of the eroding particles or chemical element of the eroding particles, kinetic energy distribution or mean kinetic energy of eroding particles, charge per eroding particles, particle mass of the eroding particles and angle of incidence of the eroding particle beam relative to the overlapping area.

3. The method according to claim 1 or 2, wherein applying the first particles comprises vaporizing a substance by heating, by applying a vacuum or by a combination thereof, exposing charged particles or ions to an electrical field, operating an ion gun directed onto a target, irradiating particles or a target with charged particles or ions, sputtering a target, performing cathodic arc deposition, or providing a plasma to the substrate, wherein applying the first particles causes deposition of charged or uncharged particles onto the substrate, and
wherein emitting the eroding particles comprises accelerating charged particles, exposing charged particles or ions to an electrical field, operating an ion gun, or irradiating charged particles or ions onto the substrate, and wherein emitting the eroding particles causes removal of first particles, removal of particles of the substrate from the substrate surface, or a combination thereof.

4. The method according to one of the preceding claims, the substrate comprising a chemical element SUB, an alloy SUB or a compound SUB and the first particles comprising a chemical element SURF, wherein SURF is identical with SUB, is soluble in SUB, or is insoluble in SUB.

5. The method according to one of the preceding claims, the method comprising emitting a dual function particle beam (1, 1'), a first part of the dual function particle beam providing a sputter particle beam (1) irradiating a target surface (S3) thereby eroding the target surface, the target surface (S3) thereby releasing the first particles (3) towards the substrate surface (2), a second part of the dual function particle beam (1 1') constituting the eroding particle beam directly irradiating the substrate surface (2).

6. The method according to one of the preceding claims, wherein applying the first particles (3) onto the substrate surface comprises applying the first particles with a particle density or flux density varying along the overlapping area providing a varying positive particle flux component on the substrate surface (2) varying with the position on the substrate surface, thereby forming a thickness gradient provided by a respective distribution of first particles on the substrate surface.

7. The method according to one of the preceding claims, wherein the first particles (3) are applied by a flow of first particles having a cross section increasing along a first propagation direction along which first particles are transported to the substrate surface (2), the first propagation direction being inclined to a normal of the overlapping area by an angle between 0° and 90° or between -90° and 0°.

8. The method according to one of the preceding claims, wherein eroding particle beam (1') is emitted along a second propagation direction of the eroding particle beam, the second propagation direction of the eroding particle beam being inclined to a normal of the overlapping area by an angle between 0° and 90° or between -90° and 0°.

9. The method according to one of the preceding claims, wherein a first propagation direction of the first particles or an averaged first propagation direction of at least a part of the first particles (3) is inclined to a second propagation direction of the eroding particle beam (1').

10. The method according to one of the preceding claims, wherein applying the first particles (3) onto the substrate surface (2) and emitting the eroding particles (1') towards the substrate surface (2) provide in the overlapping area a coverage of the substrate or a fluence of less than $5 \cdot 10^{16}$ particles/cm^2, less than $1 \cdot 10^{16}$ particles/cm^2, less than $5 \cdot 10^{15}$ particles/cm^2, less than $1 \cdot 10^{15}$ particles/cm^2, less than $5 \cdot 10^{14}$ particles/cm^2, or less than $1 \cdot 10^{14}$ particles/cm^2 of the first particles.

11. The method according to one of the preceding claims, wherein applying the first particles comprises sputtering a target surface (S3), the target surface being inclined to the overlapping area irradiated by the eroding particle beam (1'), and wherein sputtering the target surface comprises directing a sputter particle beam (1) onto the target surface (S3), the sputter particle beam (1) originating from a particle source identical with a source emitting the eroding particle beam or from a sputter particle source distinct and spaced apart from the source emitting the eroding particle beam.

12. The method according to claim 5 or 11, the sputter particle beam comprising a beam of inert gas ions with a kinetic energy of 0.5 keV – 10 keV or 1 keV – 5 keV or lower kinetic energies not higher than 0.5 keV, 0.2 keV or 0.1 keV, or a kinetic energy of 10 – 100 keV or 100keV - 500 keV, and a fluence of $1 \cdot 10^{15}$ ions/cm^2 – $1 \cdot 10^{19}$ ions/cm^2 or $1 \cdot 10^{16}$ ions/cm^2 – $1 \cdot 10^{18}$ ions/cm^2

13. The method according to one of the preceding claims, wherein the substrate surface or the overlapping area of the substrate surface (2) extends in a substrate plane and the first particles are supplied from a target surface (S3) extending in a target plane, the target plane abutting the substrate plane in the overlapping area and being inclined to substrate plane in an angle between 0 ° and 90 ° or between 0 ° and -90 °.

14. The method according to one of the previous claims, wherein the resulting cumulative flux forms a thin layer of mixed materials or an alloy at the substrate surface; or provides a homogenous mixture of material of the first particles and material of the substrate surface; or forms a binary system with one common phase comprising the material of the substrate surface and the material of the first particles miscible therein; or provides a compound of the first particles and the substrate surface, the compound forming a continuous layer, nano-composites or clusters; or provides a system of two distinct phases formed of the material of the first particles not miscible in the material of the substrate surface and material of the substrate surface, the material of the first particles forming a separate layer remaining on the substrate surface as continuous surface layer or disintegrated as islands or clusters at the surface; or provides a lattice different to the lattice of the substrate underlying the substrate surface for the case that the material of the first particles being identical to the material of the substrate surface.

15. A target device for a particle beam (1, 1') with a beam cross section area, the target comprising a target surface (S3) and a substrate surface (2) constituted by a substrate; the beam cross section area covering both, the target surface as well as the substrate surface; the target surface (S3) being inclined to the substrate surface (2) in an angle between 0 ° and ± 90°, the target surface (S3) comprising a target material being adapted to be eroded by the particle beam, the target material comprising a chemical element SURF, the substrate comprising a chemical element SUB, said chemical element SURF being identical with SUB, being soluble in SUB or being insoluble in SUB.

16. The target device according to claim 15, further comprising an alignment device aligning the particle beam or an emitter of the particle beam with the target surface and with the substrate surface, the particle beam having direction of propagation inclined to a normal of the substrate surface by an angle α, with $0° < \alpha < \pm 90°$ and inclined to a normal of the target surface by an angle β, with $0° < \beta < \pm 90°$, β being equal to α, or with α being 0° or $\alpha \leq 30°$, $\leq 20°$, $\leq 10°$, $\leq 5°$ or $\leq 2°$ and β being $\geq 30°$, $\geq 45°$, $\geq 60°$, $\geq 70°$, $\geq 75°$, $\geq 78°$, $\geq 80°$, $\geq 82°$ or $\geq 84°$.

17. The target device according to claim 15 or 16, the substrate surface (2) being arranged to receive the particle beam (1, 1'), the particle beam impinging substantially perpendicular onto the substrate surface (2), the target surface being inclined to the substrate surface in an angle $< 90°$ and $\geq 30°$ or $\geq 45°$.

18. The target device according to one of claims 15 - 17, further comprising a support element supporting the substrate, a support element supporting a target constituting the target surface (S3) and an alignment device for arbitrarily aligning or inclining the target with regard to the substrate (2), the target with regard to the particle beam or the substrate with regard to the particle beam.

19. A device for surface treatment of a substrate surface (2) by particle irradiation, comprising a first particle source (S3) and an eroding particle beam source (S1), the first particle source (S3) being arranged apply first particles onto an overlapping area of the substrate surface (2), the eroding particle beam source (S1) being arranged for emitting eroding particles onto the same overlapping area, the first particle source (S3) being arranged to provide a positive particle flux component on the substrate surface; the eroding particle beam source (S1) being arranged to provide a negative particle flux component on the substrate surface; the first particle source (S3) and the eroding particle beam source (S1) facing the same overlapping area and supplying particles providing a cumulative non-positive flux in the overlapping area.

20. The device according to claim 19, the first particle source (S3) comprising an oven, a sputter target, a sputter target with an associated ion beam source directed onto the sputter target, or an ion gun directed onto a sputter target, a cathodic arc deposition system or a plasma generator, and the erosion particle beam source comprising an ion beam source or ion gun adapted for providing ions with an energy causing erosion on the substrate surface.

21. The device according to claim 19, the first particle source (S3) being having a first input for particle delivery adjustments, the first particle source being an active particle source, and the eroding particle beam source having a second input for particle emission adjustments, independent from the first input.

22. The device according to claim 19 or 20, further comprising a dual function particle beam source providing a dual function particle beam (1, 1') comprising a sputter particle beam (1) as well as an erosion particle beam (1'), both beams (1, 1') coextending along a joint propagation direction, the device further comprising a target surface (S3) onto which the sputter particle beam (1) is directed and which provides the first particle source (S3); the target surface (S3) as a well as the substrate surface (2) being aligned vis-à-vis the dual function particle beam source to jointly irradiate both, the target surface and the substrate surface, the first particle source (S3) being a passive beam source.

23. The device according to claim 19, further comprising the target device of one of claims 15, 16, 17 or 18, the target device comprising the target surface and the substrate surface.

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24. The device according to one of claims 19 - 23, further comprising a first alignment device for aligning or inclining the first particle source with regard to the overlapping area of the substrate, and a second alignment device aligning or inclining the eroding particle beam source with regard to the overlapping area of the substrate, the first and
10 the second alignment devices being arranged to be operated independently from each other.

25. The device according to one of claims 19-24, the first particle source (S3) comprising an emitting surface or a target surface arranged to emit a flow of first
15 particles (3) with a cross section increasing along a propagation direction along which first particles (3) are transported to the substrate surface, the propagation direction being inclined to a normal of the overlapping area by an angle between 0° and 90°, between 30° and 84°, between -90° and 0° or between -84° and -30°.

20 26. The device according to one of claims 19-25, wherein the first particle source (S3) and the eroding particle beam source (S1) are arranged with respect to the overlapping area in distinct solid angles of incidence or distinct angles of incidence.

27. A method for dosing the radiation of at least a first particle source (S3) and at least
25 an erosion particle beam source (S1) for surface treatment of a substrate surface (2), the first particle source applying first particles (3) onto an overlapping area of the substrate surface (2), which is irradiated by the erosion particle beam source (S3), the method comprising:
providing input requirements related to a desired amount of net erosion of the
30 overlapping area, the amount of net erosion in the overlapping area being non-negative;
providing the operational parameters for a steady state of particles applied by the first particle source onto the overlapping area by providing a relative mean coverage f, with

35

$$f = \ln (1/(1 - J_d / (J_e \cdot Y_s))$$

J_d being a flux of first particles provided by the first particle source to the overlapping area;

J_e being a flux of eroding particles provided by the eroding particle beam source to the overlapping area; and

Y_s being the sputter yield associated with the eroding particles;

setting J_d and J_e with a given Y_s to provide f in a range of $0.001 \leq f < 4$ or in a range of $0.001 \leq f < 1$, the relative mean coverage referring to 10^{15} atoms/cm^2 as an absolute reference;

operating the first particle source (S3) with J_d and operating the erosion particle beam source (S1) with J_e.

28. The method according to claim 27, further comprising: providing input requirements related to a desired degree of roughness in the overlapping area;

if a desired degree of roughness is higher than the roughness of the surface substrate, selecting a particle material for the first particles, which is insoluble in a material of a substrate constituting the substrate surface (2);

if a desired degree of roughness is lower than the roughness of the surface substrate (2), selecting a particle material for the first particles, which is soluble in the material of the substrate constituting the substrate surface (2).

29. The method according to claim 27, further comprising: providing input requirements related to a desired degree of erosion in the overlapping area;

if a particle material of the first particles (3) is soluble in a material of a substrate constituting the substrate surface (2), providing a decreasing coverage f for an increasing desired amount of net erosion and providing an increasing coverage f for a decreasing desired amount of net erosion; and

if the particle material of the first particles (3) is insoluble in the material of the substrate constituting the substrate surface, providing an increasing coverage f for an increasing desired amount of net erosion and providing a decreasing coverage f for a decreasing desired amount of net erosion.

30. Computer program product comprising a computer program executable by a processor associated therewith, the computer program, together with the processor, providing the method of one of claims 27 - 29 when is executed by the processor.

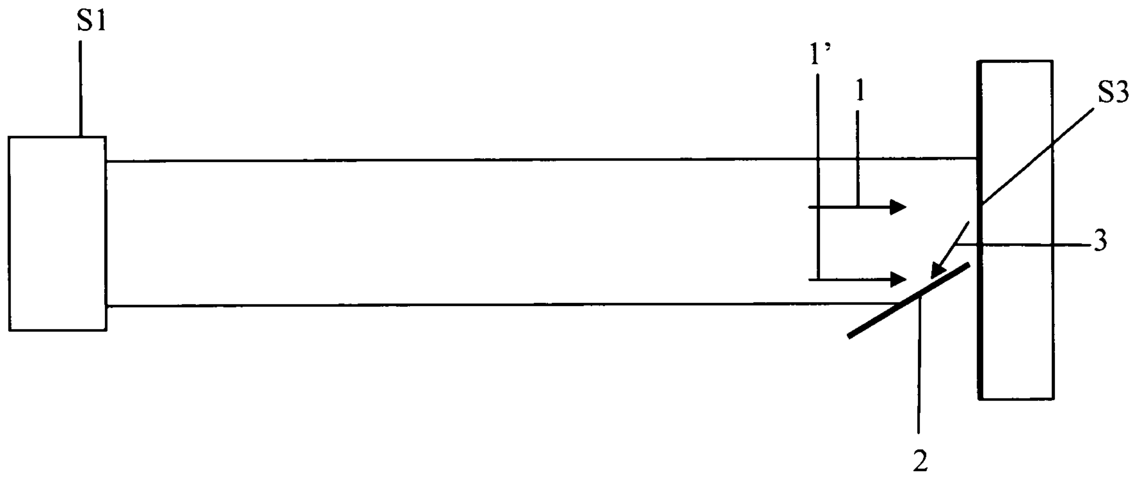

Fig. 1a

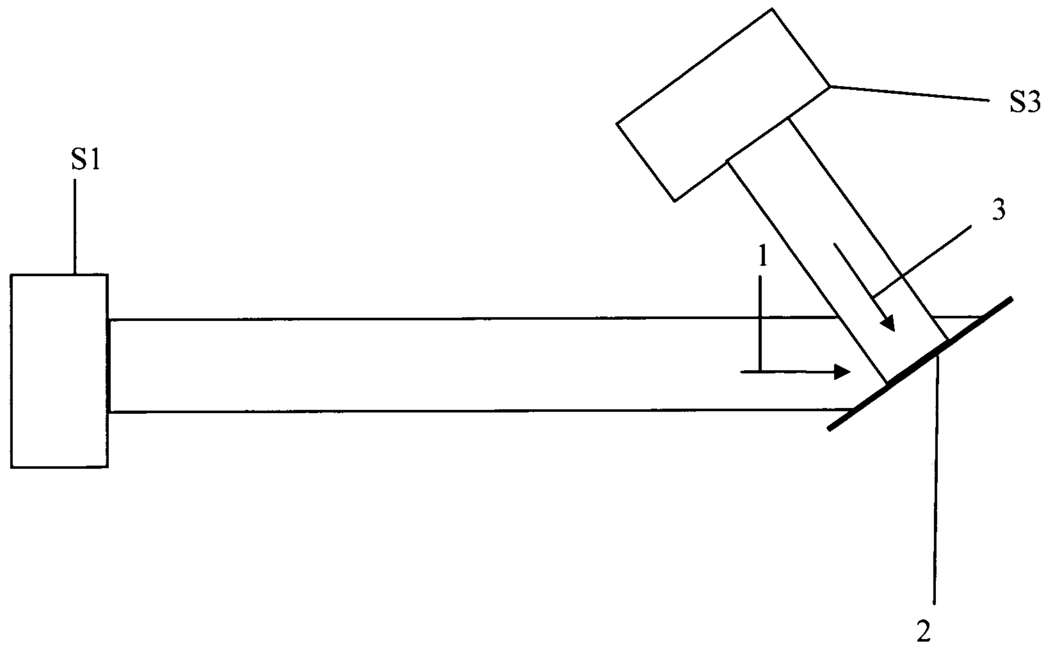

Fig. 1b

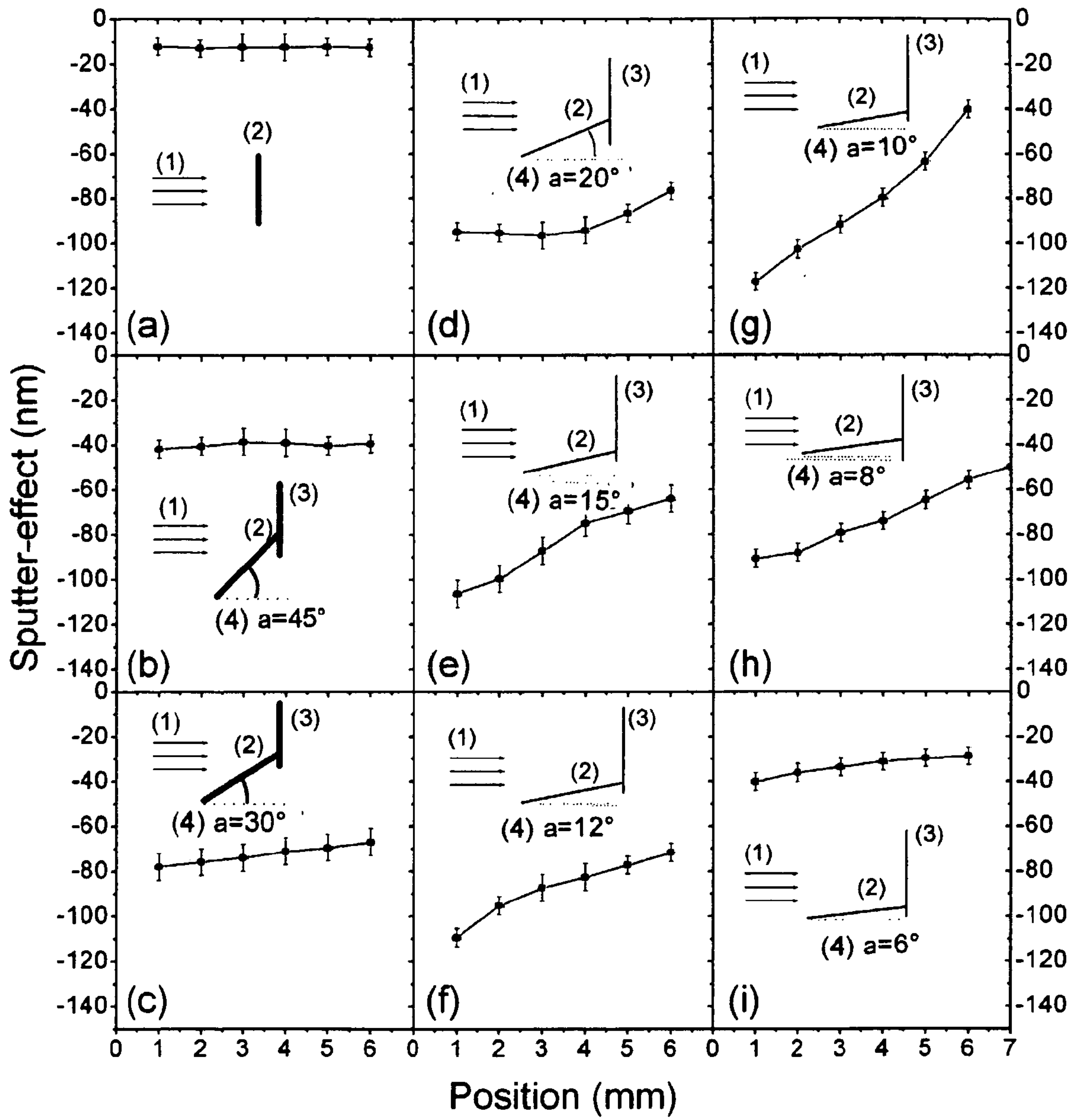

Fig. 2

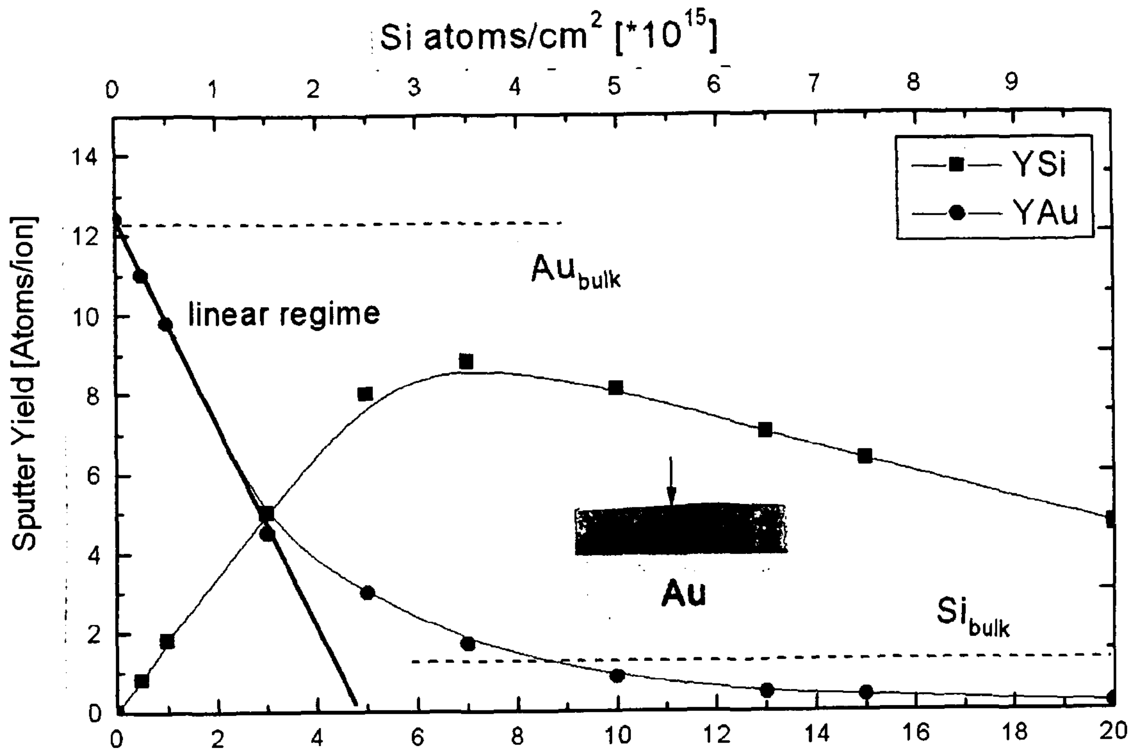

Fig. 3

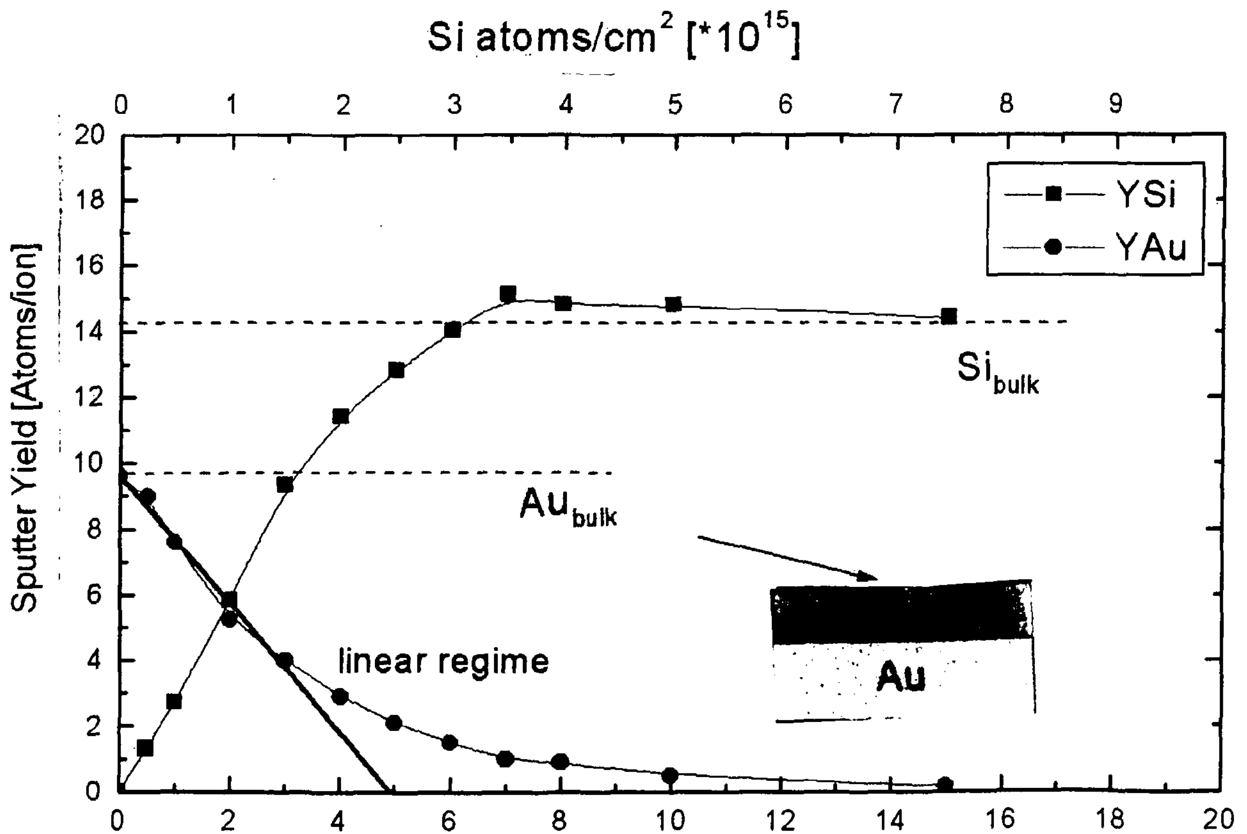

Fig. 4

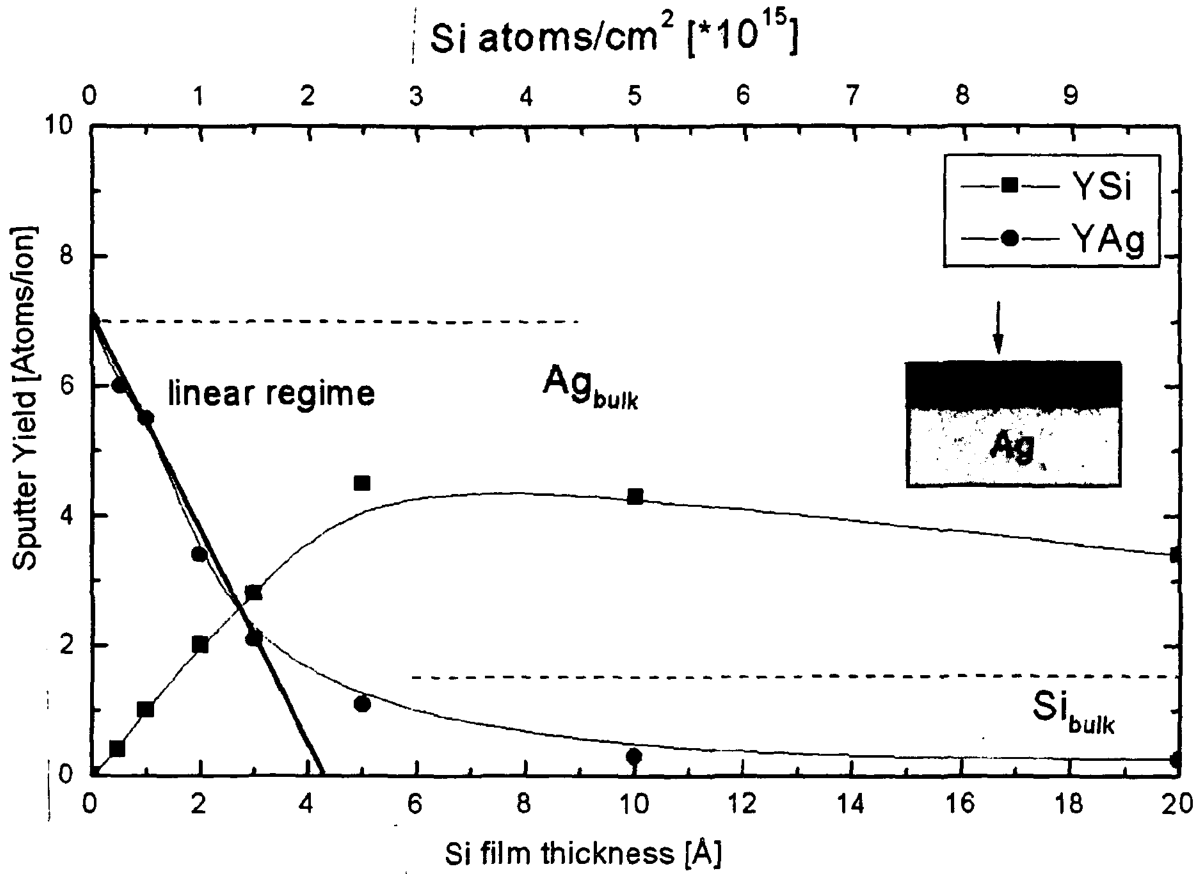

Fig. 5

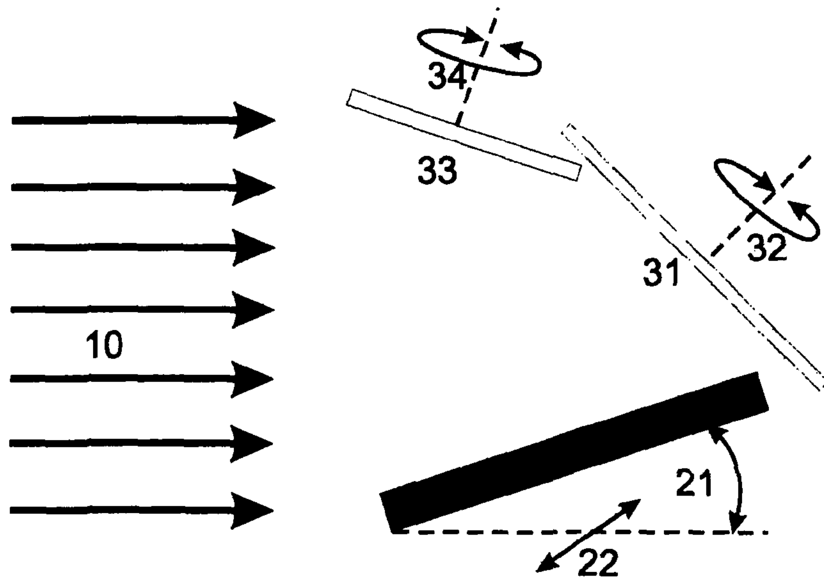

Fig. 6

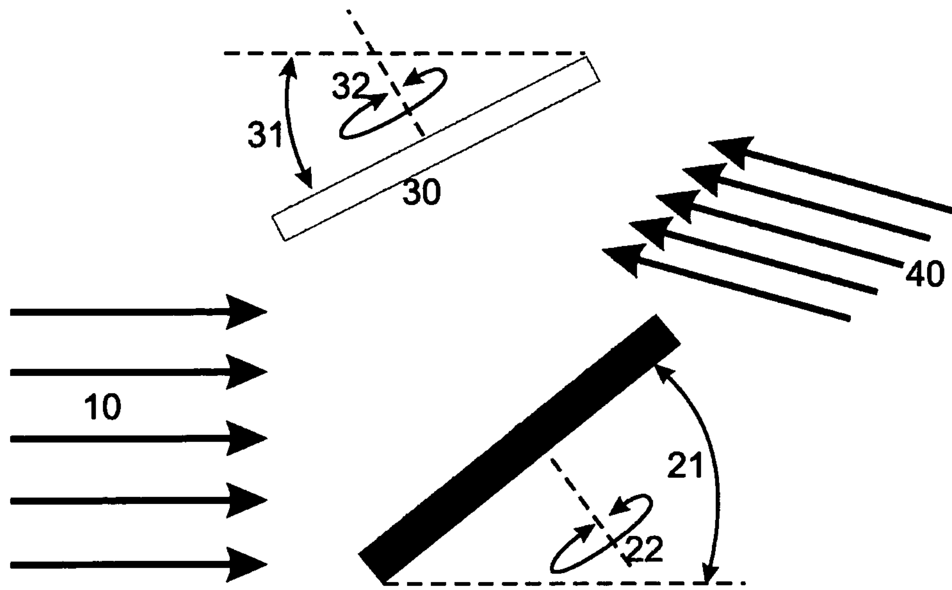

Fig. 7

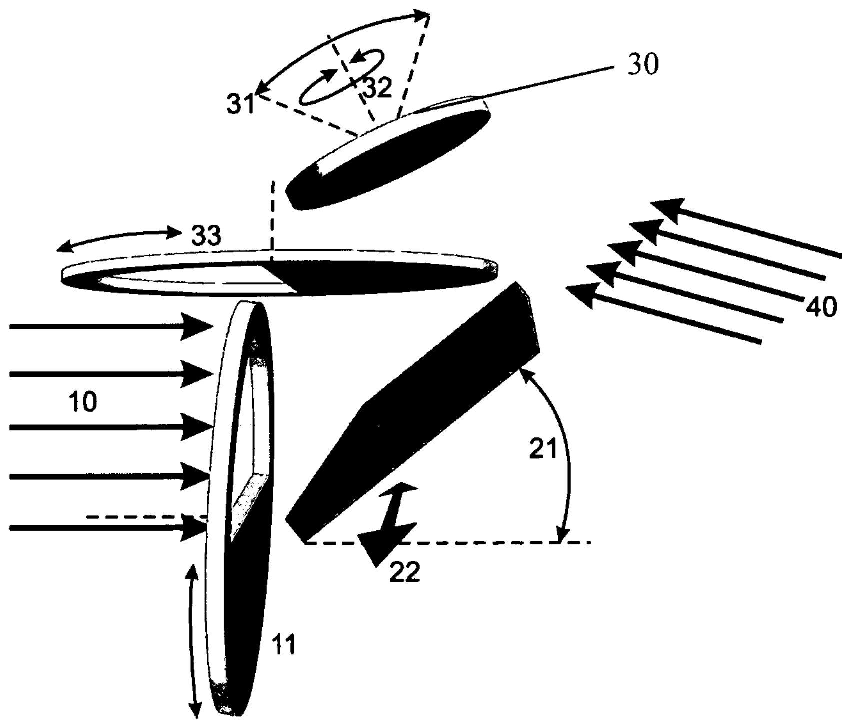

Fig. 8

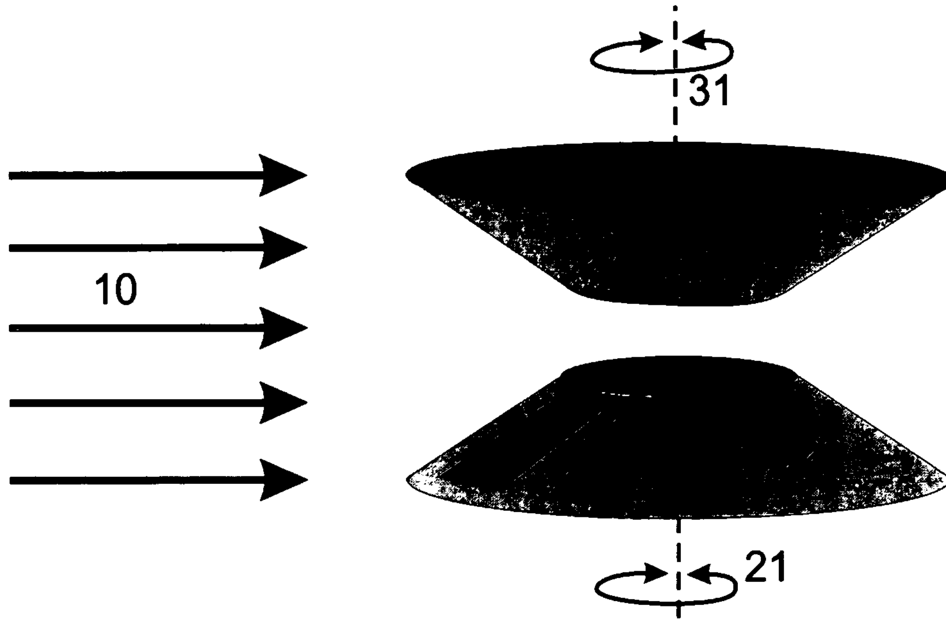

Fig. 9