On-resonance self-organization of nanostructures

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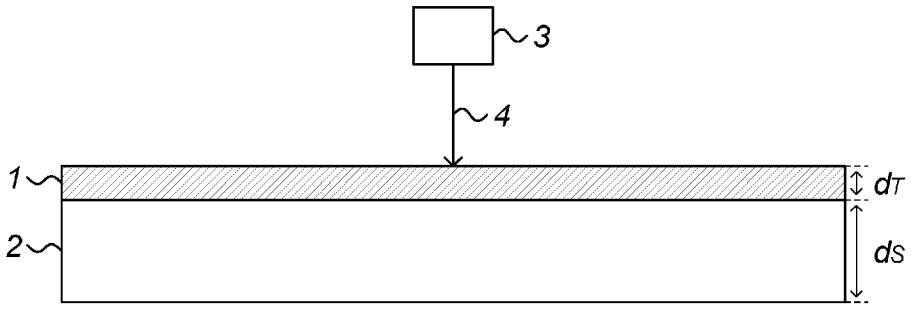

Fig. 1b

(57) Abstract: Disclosed is a method for self-organization of a nanostructure, comprising the steps of, providing a narrow-band light source having a center wavelength; providing a film on a substrate, said thin film having a film thickness, said film thickness being in the range from 0.9 to 1.1 times a Fabry Perot resonance condition thickness for said center wavelength; and irradiating said film, the irradiating comprises using said narrow-band light source to induce self-organization of said film, thereby obtaining nanostructures. A product comprising a substrate and nanostructures produced by said method is further disclosed.

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ON-RESONANCE SELF-ORGANIZATION OF NANOSTRUCTURES

Field of the invention

[0001] The present invention relates to a method for self-organization of nanostructures. Furthermore, the invention relates to a product comprising a substrate and nanostructures produced by this method.

Background of the invention

As technology advances so does the needs for complex material structures. The use of for example nanostructured materials has increased greatly over the course of the last decades, and today many consumer products utilize nanostructured materials to some extent.

Nanostructured materials may be created using lithographic techniques or even by use of lasers.

In an article (*Advanced Materials & Processes (2013), 171(7), 22-26*) a method is disclosed for fabricating metal nanostructures with pulsed laser dewetting self-assembly. The article discloses that a metallic thin film is deposited in a substrate and subsequently irradiated with laser pulses, whereby desired nanostructures are achieved by careful control of the number of laser pulses.

A disadvantage of such a method is that irradiation of the thin film by even a few extra unintentional laser pulses may result in nanostructures exhibiting morphologies that are different from what was planned for.

Therefore, is required a method of irradiating a film to create nanostructures which are reproducible in the sense that application of extra unintentional irradiation does not change the morphology of the nanostructures substantially from what is planned for.

Summary of the invention

[0002] The invention relates to a method for self-organization of nanostructures, comprising the steps of; providing a narrow-band light source having a center

wavelength; providing a film on a substrate, said film having a film thickness; said film thickness being in the range from 0.9 to 1.1 times a Fabry Perot resonance condition thickness for said center wavelength; and irradiating said film, said irradiating comprises using said narrow-band light source to induce self-organization of said film, thereby obtaining nanostructures.

[0003] Thereby is provided an advantageous new way of forming nanostructures in a film in a manner which is reproducible. When the film thickness of the film is in the range from 0.9 to 1.1 times a Fabry Perot resonance condition thickness for the center wavelength is achieved an advantageous way of absorption of light in the film. As long as the film thickness is in close proximity to the Fabry Perot resonance condition thickness, light from the narrow-band light source is resonantly absorbed by the film to some degree, with the strongest absorption occurring when the film thickness corresponds to the Fabry Perot resonance condition thickness. However, as light is absorbed, and the film undergoes a restructuring through self-organization of the film material to produce nanostructures, the effectiveness of the absorption of light from the narrow-band light source decreases. Thereby, is achieved an irradiation process which converges the self-organization of the film towards nanostructures of a specific morphology. In this sense, the irradiation process may be regarded as a feedback-controlled irradiation process where even unintentional irradiation has a negligible effect on the morphology of the nanostructures since the morphology of the nanostructures features local thicknesses deviating from the Fabry Perot resonance condition thickness, and thus the effectiveness of the resonant absorption becomes small to negligible.

[0004] Because the irradiation process in itself is feedback-controlled, it becomes easy to control the irradiation process since a meticulous measure of the amount of energy irradiated at the film is not needed, i.e. irradiation by even an extra unintended amount of energy has a small to negligible effect on the emerging nanostructures. In other words, the obtained nanostructures are not capable of further absorbing light from the narrow-band light source at the center wavelength through resonant

absorption of light. Because of this inherent feedback mechanism in the irradiation process, it is possible to produce nanostructures in a predictable manner.

[0005] In the present context the nanostructures are produced by said method, either, in one embodiment, directly by the step of irradiating the film by the narrow-band light source or, in another embodiment, by further irradiation by an additional narrow-band light source. This does not exclude that further post-processing is applied to the formed nanostructures.

[0006] In this context the term "film" is understood as a layer of material ranging from a few nanometers to several micrometers in thickness. A "film" in the present context may also be referred to as a thin film.

[0007] In this context the term "nanostructures" is understood as features having at least one dimension, in the plane of the film, which is on the nanometer scale, such as in the range of a few nanometers to several hundreds of nanometers. From this, it follows that a film is not a nanostructure. The nanostructures may form part of a larger surface-supported structure comprising a plurality of nanostructures.

[0008] In this context the term "substrate" is understood as a base material suitable for supporting a film. In this sense, the substrate is a base material on which a deposition process may be conducted in order to produce a film. Not only does the substrate support the film, it also facilitates a surface onto which the film adheres. The surface morphology of a substrate is of great importance to a deposition process because it may affect the growth process of the film and thereby also the morphology of the resulting film.

[0009] The formation of nanostructures in a film is possible through a process of self-organization induced through melting and dewetting of the film material. In such a process, a part of the film is melted such that the film material is liquified, and the liquified film then dewets, i.e. uncovers/exposes some areas of the substrate through structural material agglomeration. Subsequently the liquified film material solidifies into nanostructures having specific morphologies dictated by characteristics of the material as well as characteristics relating to the process. The morphology of the

nanostructures may have been influenced by intermolecular forces, interfacial forces, thermal gradients, chemical reactions as well as concentration gradients. The self-organization process may be thermally activated, such as opto-thermally activated where the energy required for melting of the film is provided through absorption of light from a light source. Absorption of light may advantageously be provided through resonant absorption of light.

[0010] The film on the substrate may act as an optical resonator. An optical resonator, also referred to as a resonating cavity or optical cavity, is an arrangement of reflecting surfaces, such as mirrors, that forms a standing wave cavity resonator for light waves. An example of such an optical resonator is a plane-parallel, or optical Fabry Perot resonator, comprising two opposing flat reflective surfaces. An optical Fabry Perot resonator may be realized by a film where the interfaces between the film and the surrounding media acts as reflective surfaces. In this sense, the film of the present invention acts as an optical Fabry Perot resonator, which may be in resonance with an external light field generated by the narrow-band light source.

[0011] In this context, the term Fabry Perot resonance condition thickness is understood as a theoretical film thickness which fulfils the conditions for Fabry Perot resonance. The resonance condition is

$$m\lambda_0 = 2dn, \quad m = 1,2,3, \ldots$$

where m is an integer, λ_0 is the wavelength of the light which is incident on the film, d is the thickness of the film, and n is the refractive index of the film material. The above formula may be rearranged to express the Fabry Perot resonance condition thickness, also referred to as d_{FP}

$$d_{FP} = \frac{m\lambda_0}{2n}$$

Thus, by knowing the center wavelength of the narrow-band light source and the refractive index of the film material it is possible to predict a Fabry Perot resonance condition thickness for which the film, or Fabry Perot resonator, may absorb incident

light from the narrow-band light source most effectively. Similarly, a required center wavelength may be calculated when knowing the film thickness and the refractive index of the film material.

Thus, in the present context, said film (1) has a film thickness (dT) within a range of 0.9 to 1.1 times a Fabry Perot resonance condition thickness for said center wavelength, wherein said Fabry Perot resonance condition thickness d_{FP} is given by,

$$d_{FP} = \frac{m\lambda_0}{2n}$$

where m is an integer, λ_0 is said center wavelength, d is a thickness of said film, and said film is made from a film material, where n is a refractive index of said film material at said center wavelength.

[0012] In this context, the term "narrowband light source" should be understood as a light source emitting light having a highest intensity at a center wavelength and emitting light of less intensity in a narrow band of frequencies around the center wavelength. The emission spectrum of such a narrowband light source may conveniently be described as having a center wavelength with an associated FWHM (Full Width at Half Maximum) value, describing the change in wavelength relative to the center wavelength for which the intensity of emitted light is reduced by fifty percent. In this context, a narrowband light source is a light source having an emission spectrum characterized by having a small FWHM-value.

[0013] In an embodiment of the invention said narrowband light source has a FWHM-value below 20 nm, such as below 10 nm, such as below 5 nm, such as below 1 nm, such as below 0.1 nm.

[0014] In an embodiment of the invention, said narrowband light source has a FWHM-value in the range of 0 to 20 nm, such as in the range of 0 nm to 10 nm, such as in the range of 0 nm to 5 nm, such as in the range of 0 nm to 1 nm, for example in the range of 0 nm to 0.1 nm.

[0015] It is advantageous to use a narrow-band light source characterized by having a low FWHM-value since then only light within a narrow range of wavelengths contribute to the self-organization process of the film. Reducing the range of contributing wavelengths increases the predictability of the method since then the risk of having light fulfilling other resonance conditions may be reduced.

[0016] As the film, having an initially well-defined film thickness, is processed by irradiation with light from the narrow-band light source only a small area, i.e. a processing area, of the entire film surface is processed at any given time due to the limited spot size of light emitted by the narrow-band light source. This local processing of the film results in local self-organization of the film, such that nanostructures are obtained locally in the film.

[0017] As soon as the morphology of the nanostructures changes in such a way that they feature local film thicknesses, at specific locations in the plane of the film, that are no longer in close proximity to the Fabry Perot resonance supporting film thickness d_{FP}, absorption of light becomes less pronounced at these locations, and therefore further restructuring of the nanostructures becomes less pronounced . In this sense, the self-organization of the film can be regarded as a feedback-controlled self-organization process, in which the process of creating nanostructures slows down as local thicknesses of the emerging nanostructures increasingly differs from the thickness d_{FP}. This feedback-mechanism ensures that the self-organization of the nanostructures may converge towards a final morphology throughout the irradiation with light from the narrow-band light source, and thereby predictable nanostructures may be created.

[0018] In an embodiment of the invention, said film thickness is in the range from 0.95 to 1.05 times a Fabry Perot resonance condition thickness for said center wavelength.

[0019] In an embodiment of the invention, said film thickness is in the range from 0.98 to 1.02 times a Fabry Perot resonance condition thickness for said center wavelength.

[0020] In an embodiment of the invention, said film thickness is in the range from 0.99 to 1.01 times a Fabry Perot resonance condition thickness for said center wavelength.

[0021] In an embodiment of the invention said film thickness corresponds to a Fabry Perot resonance condition thickness for said center wavelength.

[0022] In an embodiment of the invention said step of providing said film comprises a step selected from the group consisting of PVD-step, CVD-step, ALD-step, PLD-step, spin-coating step, thermal deposition step and combinations thereof.

[0023] In this context the terms “PVD”, “CVD”, “ALD” and “PLD” is understood as physical vapor deposition, chemical vapor deposition, atomic layer deposition and pulsed laser deposition respectively. These terms refer to different techniques of deposition.

[0024] Providing said film using steps from any of the above techniques of film deposition is advantageous in that a film may be provided on a substrate in a controllable manner, such that the film obtains a well-defined thickness which is essential for the predictability of the morphology of the nanostructures emerging through the irradiation with light from said narrow-band light source.

[0025] In an embodiment of the invention said method comprises a further step of irradiating said nanostructures using a second narrow-band light source having a second center wavelength to induce further self-organization of said nanostructures.

[0026] Irradiating said nanostructures using a second narrow-band light source having a second center wavelength is advantageous in that a restructuring of the nanostructures through self-organization of the nanostructures may be performed such that modified nanostructures may be created. The modified nanostructures, emerging through irradiation of the nanostructures using the second narrow-band light source, may exhibit a more complex morphology than the morphology of the nanostructures which emerged after irradiation with the narrow-band light source. The self-organization of the nanostructures into modified nanostructures may only occur as

long as Fabry Perot resonance conditions are fulfilled for the nanostructures using the second narrow-band light source or when local thicknesses of the nanostructures are in close proximity to the Fabry Perot resonance condition thickness, such as in the range of 0.9 to 1.1 times the Fabry Perot resonance condition thickness. Accordingly, the narrow-band light source referred to in the above paragraphs may also be considered as a first narrow-band light source.

[0027] In an embodiment of the invention said step of irradiating said film using a narrow-band light source comprises moving said film, residing on said substrate, relative to said narrow-band light source. In an embodiment said relative movement of said film with respect to said narrow-band light source may be performed by moving said film using a movable and controllable stage while keeping said narrow-band light source fixed in space. Said film on said substrate, may be fixated by fixating means to a stage capable of moving and positioning itself in a plane. Said fixating means may comprise clamping of the combined film and substrate onto the movable and controllable stage, suction of the substrate and film on to the movable and controllable stage by use of a vacuum connection, or by use of double-sided tape taping the substrate and film to the movable and controllable stage.

[0028] Moving the combined film and substrate relative to the narrow-band light source is advantageous in that an area greater than the processing area of the narrow-band light source may be processed by e.g. raster scanning the combined film and substrate relative to the narrow-band light source. Thereby an area of nanostructures extending beyond the processing area of the narrow-band light source may be produced. Keeping the narrow-band light source stationary while moving the film and substrate on a movable and controllable stage may be advantageous when using a sensitive narrow-band light source where the performance of the narrow-band light source may be influenced by e.g. movements of the narrow-band light source.

[0029] In an embodiment of the invention said method comprises a step of measuring said film thickness prior to irradiating said film using said narrow-band light source.

[0030] Measuring the film thickness prior to irradiating said film using a narrow-band light source is advantageous in that it may be confirmed whether the film provided on the substrate has a film thickness which is at, or in proximity to, the theoretical thickness needed in order for the Fabry Perot resonance condition to be fulfilled.

[0031] In an embodiment of the invention said step of measuring said film thickness may be performed by use of optical means such as interferometry, spectrometry, ellipsometry with a single well-defined wavelength or ellipsometry using several wavelengths. Using measuring techniques based on optical means is advantageous in that such methods are non-destructive, and therefore the use of such techniques does not result in any damages of the film which may affect the outcome of the irradiation of the film using the narrow-band light source.

[0032] In an embodiment of the invention, said method comprises a step of estimating said film thickness. Said film thickness may be estimated based on e.g. previous film depositions where deposition parameters have been correlated to measured film thickness, thereby establishing an empirically based relationship between deposition parameters and resulting film thickness. By establishing such relationships, it is possible to estimate a thickness of a film produced using a given set of deposition parameters.

[0033] In an embodiment of the invention said film is obtained by pre-treating a precursor film.

[0034] By obtaining said film by pre-treating a precursor film it is understood that the step of providing said film comprises pre-treating a precursor film to obtain said film. In this context, the term “precursor film” is understood as a pristine film which is left unchanged after its deposition.

[0035] In this context, the term “pre-treatment” is understood as any treatment occurring after deposition of the film and before irradiation of the film. A pre-treatment may for example be a non-destructive process such as a cleaning process or a more destructive process which affects the morphology of the film.

[0036] Pre-treating the film may have several advantages. For example, a pristine film may, depending on the deposition technique used to make the film, have a non-ideal surface roughness such that the film thickness varies locally across the film, and therefore the central wavelength of the narrow-band light source may not perfectly fulfil the resonance condition across the entire film. By smoothening the film, using a pre-treatment process, the surface roughness of the film may be reduced such that the film thickness obtains a smaller variation across the film. This results in more predictable morphologies of the nanostructures emerging after light irradiation of the film.

[0037] In an embodiment of the invention said pre-treating comprises subjecting said precursor film to a chemical treatment, such as chemical etching.

[0038] By a chemical treatment may be understood methods of chemical nature such as chemical mechanical polishing, chemical mechanical planarization and lithography etching, using wet etching, dry etching or reactive ion etching. Using a chemical treatment as a pre-treatment of said film is advantageous in that for example a film having a very smooth surface may be realized.

[0039] In an embodiment said step of providing a film supported by a substrate comprises a step or pre-treating said substrate prior to application of said film on said substrate. The step of pre-treating the substrate may comprise subjecting the substrate to a chemical treatment such as chemical mechanical polishing,

[0040] In an embodiment of the invention said film thickness is below 1000 nm, such as below 600 nm, such as below 300 nm.

[0041] In an embodiment of the invention said film thickness is in the range 50 nm to 1000 nm, such as in the range of 100 nm to 600 nm, for example in the range of 150 nm to 300 nm.

[0042] Keeping the film thickness low is advantageous in that a limited number of resonant wavelengths are supported by the film for a given narrow-band light source. As the film thickness increases, the resonance condition may be fulfilled by an

increasing number of wavelengths, all of which become closer spaced in relation to each other, and thereby the characteristics of Fabry Perot resonance absorption at a particular wavelength is diminished.

[0043] In an embodiment of the invention said film is selected from the group of materials consisting of metals, alloys, semiconductors such as titanium dioxide, or any combination thereof.

[0044] Having the film made of a metal, an alloy, a semiconductor or any combination thereof, is advantageous in that the film may have a refractive index substantially greater than the refractive index of air. Using a film having a high refractive index is advantageous in that a final nanostructured product exhibiting optical effects associated with a high refractive index may be obtained by irradiation.

[0045] In an embodiment of the invention, the film comprises or is made of a semiconductor material.

[0046] In an embodiment said film is selected from a material selected from the group of materials consisting of silicon, germanium, indium phosphide, titanium dioxide, gallium phosphide, gallium nitride, alloys comprising these materials, or any combination thereof.

[0047] In an embodiment of the invention, said film comprises or is made of a metal.

[0048] In an embodiment of the invention, said film comprises or is made of a material selected from the group consisting of gold, silver, aluminum, and any combination thereof.

[0049] In an embodiment of the invention, said film comprises or is made of an alloy.

[0050] In an embodiment of the invention, said film is made by a combination of metal and semiconductor.

[0051] One preferred combination of metal semiconductor may be a combination of titanium dioxide with one selected from gold, silver, aluminum, and any combination thereof.

[0052] In an embodiment of the invention said film has a refractive index of at least 2, such as at least 2.5.

[0053] In an embodiment said film has a refractive index in the range of 2 to 5, such as in the range of 2.5 to 5, for example in the range of 3 to 5.

[0054] It is understood that the refractive index of the film refers to the refractive index of the film material prior to irradiation with light from said narrow-band light source.

[0055] In an embodiment of the invention said substrate has a refractive index being at least 0.3 lower than said refractive index of said film, such as at least 0.5 lower than said refractive index of said film, such as at least 1 lower than said refractive index of said film. Having a substrate with a refractive index lower than the refractive index of the film is advantageous in that an interface between the film and substrate is formed, which interface may support reflections of light within the film.

[0056] The refractive indexes of said film and said substrate are understood as being defined at the center wavelength of said narrow-band light source. Furthermore, within the context of the present invention, a refractive index is understood as a real number. Thus, when referring to a refractive index as a complex number comprising a real part and an imaginary part, the refractive index refers only to the real part and not to the imaginary part associated with absorption of light in e.g. metals.

[0057] In an embodiment of the invention said narrow-band light source comprises a laser.

[0058] In an embodiment of the invention said narrow-band light source consists of a laser.

[0059] By the term "laser" (acronym for "Light Amplification by Stimulated Emission of Radiation") is understood a device which emits light through a process of optical amplification based on stimulated emission of electromagnetic radiation. A laser is characterized by emitting spatially coherent light, which enables a laser to project light onto a small spot area. Furthermore, a laser is typically characterized by emitting light in a narrow range of wavelengths, thus a laser is typically associated with a very small FWHM-value.

[0060] Using a laser is advantageous in that the self-organization of the film may be controlled to a high degree of precision owing to the small spot area of the laser beam. By processing a small area of the film, at any instance, a product featuring nanostructures arranged in a detailed pattern of high complexity may be created.

[0061] In an embodiment of the invention said narrow-band light source projects a light spot on said film, said light spot having a diameter in the range of 1 μm to 5 μm.

[0062] In an embodiment of the invention said narrow-band light source projects a light spot on said film, said light spot having a diameter being less than 1 μm.

[0063] In an embodiment of the invention said narrow-band light source is a pulsed light source.

[0064] By the term "pulsed light source" is understood a light source emitting light in the form of optical pulses.

[0065] Using a pulsed light source is advantageous in that a high instantaneous power is achieved without using a high average power. Thus, high instantaneous powers, used for melting and dewetting of the film, can be delivered to the film without transmission of too much average power which may lead to damaging of the film and/or substrate.

[0066] In an embodiment of the invention said pulsed light source is a pulsed laser.

[0067] In an embodiment of the invention said narrow-band light source is a continuous light source.

[0068] By the term "continuous light source" is understood a light source capable of continuous emission of light.

[0069] In an embodiment of the invention individual pulses of said pulsed narrow-band light source has a pulse energy in the range 1 nJ to 100 μJ.

[0070] In an embodiment of the invention said pulse energy of said pulsed narrow-band light source is in the range from 1 nJ to 50 μJ, such as in the range from 1 nJ to 1 μJ.

[0071] In an embodiment of the invention said narrow-band light source has a center wavelength in the range of 200 nm to 20 μm.

[0072] In an embodiment of the invention said center wavelength is in the range of 266 nm to 20 μm, such as in the range of 400 nm to 700 nm, such as for example 532 nm. Other wavelengths may also be used. For example, a center wavelength of 441.6 nm may be realized by a HeCd laser, a Nd:YAG laser may be frequency doubled to produce a center wavelength of 532 nm, and a wavelength of 694.3 nm may be realized by a ruby laser.

[0073] In an embodiment said narrow-band light source comprises at least one narrow-band LED.

[0074] Several narrow-band LED's may be used for increased light intensity.

[0075] In an embodiment of the invention the light emitted from said narrow-band light source is incident on said film at a normal angle of incidence.

[0076] By the term "normal angle of incidence" may also be understood that the beam of light is substantially perpendicular to the plane of the film.

[0077] The invention further relates to a product comprising a substrate and nanostructures produced by the method described in any of the above embodiments of the invention.

[0078] In an embodiment of the invention said film comprises a plurality of stacked layers of film material.

[0079] Thus, the film comprises at least one layer and may in certain embodiments comprise a plurality of stacked layers, such as e.g. at least two stacked layers. When using a plurality of stacked layers of film material, the conditions posed on the refractive index of the film material may preferably concern all stacked layers as the effective refractive index of the whole film. I.e., when said film comprises several stacked layers, the refractive index may preferably be understood as the effective refractive index of the whole film comprising stacked layers, as indicated by the reference to the refractive index of the film material. The effective refractive index may be measured when addressing the film comprising stacked layers as a whole.

[0080] In an embodiment of the invention said stacked layers of film material comprises layers with different refractive indexes.

[0081] In an embodiment of the invention, said stacked layers comprises at least one metal layer.

[0082] In an embodiment of the invention, said stacked layers comprises at least one semiconductor layer.

[0083] In an embodiment of the invention, said stacked layers comprises a combination of at least a metal layer and a semiconductor layer.

[0084] In an embodiment of the invention, said stacked layers comprises a combination of at least a metal layer and a titanium dioxide layer.

[0085] In an embodiment of the invention, said stacked layers comprises a combination of at least two metal layer and a titanium dioxide layer.

[0086] In an embodiment of the invention, said stacked layers comprises a combination of at a gold layer, a titanium dioxide layer, and an aluminum layer.

[0087] In an embodiment of the invention said film consists of a single layer of material.

[0088] In an embodiment of the invention said substrate comprises an insulator material, such as polymer or glass.

[0089] Non-limiting examples of glasses usably within the scope of the invention may e.g. include quartz glass and borosilicate-crown glass.

[0090] Non-limiting examples of polymers usably within the scope of the invention may e.g. various polymer materials that are preferably transparent, such as poly(methyl methacrylate) (PMMA).

[0091] The invention relates in a further aspect to a product comprising a substrate and nanostructures, the nanostructures being characterized by showing a peak with a width of between 0.1 and 4.0 μm^{-1} of an intensity curve along a radial line in a reciprocal space representation of a SEM image of said product.

[0092] In the present context, the intensity curve is understood as a curve showing the intensity along a radial line, i.e. a straight line through the center of the reciprocal space representation of the SEM image of said product.

[0093] In the present context the width of the peak is understood as the full width at half maximum (FWHM).

[0094] In an advantageous embodiment of the invention, the nanostructures comprise at least one selected from the list consisting of gold, silver, aluminum, semiconductor material such as titanium dioxide, and combinations thereof.

[0095] In an advantageous embodiment of the invention, the material induces a phase shift in 160-200 degrees for normal incident light having said center wavelength.

[0096] In an advantageous embodiment of the invention, the nanostructures (6) are characterized by showing a peak with a width of between 0.2 and 2.0 μm^{-1} of an

intensity curve along a radial line in a reciprocal space representation of a SEM image of said product, such as 0.3 and 1.0 μm^{-1}.

[0097] In an advantageous embodiment of the invention, the product produced by the method according to the invention or any of its embodiments.

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The drawings

[0098] Various embodiments of the invention will in the following be described with reference to the drawings where

figs. 1a–d illustrate embodiments of the invention where a film is provided on a substrate and irradiated by a narrow-band light source to create nanostructures having a specific morphology,

figs. 2a-b illustrate embodiments of the invention where nanostructures are irradiated with a second narrow-band light source,

figs. 3a-b illustrates a providing of a film which may either be a pristine film or a film which has undergone a pre-treatment,

fig. 4 illustrates how the refractive index may change when passing through air/vacuum, film and substrate,

fig. 5 illustrates refractive indexes for selected materials as a function of wavelength,

figs. 6a-c illustrates an embodiment of the invention where it is shown how the self-organization process is feedback-controlled owing to resonance conditions,

figs. 7a-c illustrates an embodiment of the invention where a Fresnel lens is produced using the method of the claimed invention,

figs. 8 illustrates an embodiment of the invention where a product comprising the portrait of Mona Lisa is produced using the method of the claimed invention,

figs. 9A-9E shows SEM images surfaces comprising nanostructures according to embodiments of the invention,

figs. 10A-10E show corresponding reciprocal space representations made by Fast Fourier Transformation, and

fig. 11 shows an intensity curve with a full width half maximum (FWHM) indicated.

Detailed description

[0099] In the following, the terms "film" and "thin film" are used interchangeably. Furthermore, the terms "Fabry Perot resonance condition thickness" and "d_{FP}" are used interchangeably.

[0100] Figs. 1a-1d shows embodiments of the invention. The drawings serve to illustrate a method of creating nanostructures in a film 1 which is disposed on top of a substrate 2 through resonant absorption of light emitted from a narrow-band light source 3.

[0101] Referring to fig. 1a, a thin film 1 is provided on a substrate 2. The view presented in fig. 1a is a sideview, which may represent the entire width of the thin film and substrate, or merely a sideview of a section of these. The thin film 1 has an associated thickness d_T and similarly the substrate has an associated thickness d_S. For the purpose of illustration, the ratio between the thin film thickness d_T and the substrate thickness d_S is not drawn to accurately represent typical ratios used, since the thin film thickness d_T may be several orders of magnitude smaller than the substrate thickness d_S.

[0102] The thin film 1 may be of materials selected from metals, alloys or semiconductors. In the following it is assumed that the thin film 1 is made of silicon, which is a semiconductor exhibiting a high refractive index over a wide range of wavelengths. As an example, silicon exhibits a refractive index of approximately 4.2 at a wavelength of 532 nm, see fig. 5. On the other hand, the substrate 2 may be of a material having a substantially smaller refractive index than the thin film 1 at comparable wavelengths. The substrate 2 may be of glass or polymers. In the following it is assumed that the substrate 2 is made of optical glass, such as borosilicate-crown glass which has a refractive index of approximately 1.5 at a similar wavelength of 532 nm, see also fig. 5.

[0103] In this example, the thin film 1 is disposed between a substrate 2 and surrounding air or vacuum having a refractive index of approximately 1 and being substantially independent of wavelength. Thus, two interfaces exist; an interface

between air/vacuum and thin film 1 and an interface between thin film 1 and substrate 2. Due to the differences in refractive indexes, reflections of light may be possible at these interfaces. In this sense, the interfaces between air/vacuum and thin film 1 and between thin film 1 and substrate 2 may act as mirrors. This aspect is further elaborated on in relation to fig. 4.

[0104] The step of providing the thin film 1 on top of the substrate may be carried out using various coating techniques. For example, the thin film may be provided using techniques of physical vapor deposition, abbreviated PVD. These techniques constitute a large group of gas-phase and plasma-based coating processes. Common to PVD-techniques is that at least one of the components of the final coating/thin film, such as a metal or a semiconducting material like silicon, is present in solid form in the chamber in which the coating is deposited. It is thus necessary to bring this solid component into gas-phase before it can be part of a coating. This transfer of material from solid-phase to gas-phase can be performed in various ways such as by thermal evaporation or by sputtering. The thin film material, which is in gas-phase, then condenses on a substrate whereby a thin film of the thin film material is formed on top of the substrate 2.

[0105] A critical step in the self-organization of the thin film material is irradiation of the thin film 1 with light. This is illustrated fig. 1b.

[0106] In the embodiment of fig. 1b, the narrow-band light source 3 is a laser, although other types of narrow-band light sources are conceivable in other embodiments. Irradiation of the thin film 1 using a laser 3 is performed to induce morphological changes in the thin film 1 through resonant absorption of light. Although not immediately conceivable from the drawing in fig. 1b, the light beam 4 of the laser has a finite extension. The light beam may for example have a cross-sectional diameter of 1 micrometer.

[0107] Morphological changes in the thin film 1 occur due to the energy of the laser light being absorbed by the thin film 1. In this embodiment, laser light is absorbed by the thin film 1 through the process of resonant absorption. For laser light to be

resonantly absorbed, the thickness d_T of the thin film 1 has to be carefully selected in accordance with specific resonance conditions. The conditions for resonant absorption of light (or Fabry Perot resonance condition) is given by the following equation

$$d_{FP} = \frac{m\lambda_0}{2n}$$

where d_{PF} is a theoretical thin film thickness which results in the most effective resonant absorption, m is an integer, λ_0 is the central wavelength of the laser light and n is the refractive index of the thin film at the central wavelength of the laser.

[0108] Ideally, the thickness d_T of the thin film 1 is perfectly matched with the above theoretical thickness d_{PF}, however due to practical limitations, e.g. reliability of typical coating techniques, the thickness d_T of the thin film 1 may deviate slightly from the theoretically optimal and intended thickness d_{PF}, such that the effectiveness of the resonant absorption is slightly reduced. Accordingly, the effectiveness of the resonant absorption may vary across the film 1. Whenever the resonance condition is fulfilled, laser light is effectively absorbed by the thin film 1 and converted into heat which is used to locally melt and dewet the thin film 1 such that a morphological restructuring of the thin film 1 occurs. Thus, by resonantly absorbing the laser light, self-organization of the thin film material occurs such that nanostructures 6 are created by the thin film material.

[0109] Naturally, the area of the thin film where this process occurs correlates with the area of the thin film, which is irradiated by laser light 4, and thus the size of the laser beam defines the size of the processing area 5 as also seen in fig. 1c. By irradiating the thin film at one or more positions at the surface of the thin film, through e.g. raster scanning of the laser beam across the thin film surface, an extended area of the thin film surface can be processed such that macroscopic thin film products comprising nanostructures can be created.

[0110] As the thin film morphology changes locally at the processing area 5, due to irradiation, so does the local thicknesses of the thin film at the processing area. Whenever a local thin film thickness deviates from the thickness d_{PF} fulfilling the

conditions for Fabry Perot resonance so does too the effectiveness of the resonant absorption. Thus, the restructuring of the thin film 1 becomes less and less pronounced as the local thickness deviates more and more from the optimal thickness d_{PF} fulfilling the conditions for resonant absorption. In this sense the resonance absorption of light is a self-terminated process, or feedback-controlled process, which ensures that the local thin film morphology at the processing area 5 converges towards a specific morphology.

[0111] Fig. 1c shows an embodiment of the invention. The drawing shows a top-down view of the surface of the thin film 1 of figs. 1a-b as the thin film 1 is irradiated by the laser 3. The drawing shows a laser beam which is focused on a specific area 5 of the thin film 1, which from now on is referred to as the processing area 5. The sizes are not necessarily to scale, and typically the area of the thin film surface is orders of magnitude greater than the processing area 5. The processing area 5 may be moved in a plane spanned by the x-axis and the y-axis (both shown on fig. 1c) such that an extended area of the thin film surface is irradiated. The coordinates of the processing area 5 are relative coordinates with respect to the thin film 1. The relative movement of the processing area 5 with respect to the thin film 1 may be realized by moving the laser 3 while keeping the thin film 1 and its underlying substrate 2 stationary, or alternatively by moving the thin film 1 and underlying substrate 2 with respect to a stationary positioned laser 3.

[0112] Fig. 1d shows an embodiment of the invention. The drawing illustrates a sideview of a final product comprising nanostructures 6 on a substrate 2, or section of such a final product, obtained after irradiating the thin film 1 with a laser 3. As seen in fig. 1d, the thin film has undergone a restructuring, through self-organization, from a smooth continuous thin film, as shown in fig. 1a, into a self-organized structure comprising a plurality of nanoscale or submicron-scaled nanostructures 6 on the substrate 2. The nanostructures 6 shown in the figure merely serves as an example of nanostructures realized by the above irradiation method, and depending on the details concerning the irradiation, as discussed later, nanostructures 6 exhibiting different morphologies may be realized.

[0113] The laser 3 may preferably be a pulsed laser. By using a pulsed laser, it is possible to utilize high laser powers without using high average powers. Thus, high instantaneous powers, used for melting and dewetting of the thin film, can be delivered to the thin film without transmission of too much average power which may lead to damages of the thin film and/or substrate.

[0114] A pulsed laser periodically emits pulses of energy in ultra-short time durations. A pulsed light source may be characterized by peak power, average power, pulse width, pulse energy and duty cycle. To a first approximation the peak power p_{peak}, of a light pulse is defined by the pulse energy E_{pulse}, divided by the pulse width τ_{pulse}, with the pulse energy being the total energy contained in the light pulse.

$$p_{peak} = \frac{E_{pulse}}{\tau_{pulse}}$$

The average power of the pulsed light source is defined as the amount of energy E_{cycle}, released over the period of the cycle τ_{cycle}, or the product of the cycle energy E_{cycle}, and the frequency of the laser pulsing f_{cycle}

$$p_{avg} = \frac{E_{cycle}}{\tau_{cycle}} = E_{cycle} f_{cycle}$$

From these equations it is clear that reducing the pulse width the peak power can be increased and likewise increasing pulsing frequency of the light source, the average power of the light source is increased.

The average power may also be expressed using the duty cycle D_{cycle}, of the pulsed light source. The duty cycle is the percentage of how much of the time the light source is emitting light. For instance, a light source with a 5 percent duty cycle is emitting light in 5 percent of the time, over a number of cycles, and not emitting light in the remaining 95 percent of the time.

$$p_{avg} = p_{peak} D_{cycle}$$

[0115] As can be seen from the above equation, a low average power p_{avg} can be realized with high peak powers p_{peak}, by utilizing a low duty cycle D_{cycle}. Adjustment of the duty cycle is naturally realized by adjusting the pulse length τ_{pulse} as well as the pulsing frequency f_{cycle}.

[0116] When using a pulsed laser, the melting and dewetting of the thin film 1 occurs in response to each individual laser pulse, and the thin film solidifies into a specific morphology before a new laser pulse is absorbed by the thin film 1. Thus, when a specific area 5 of the thin film 1 is processed using a pulsed laser 3 the morphology of the thin film at the processing area 5 changes in response to individual laser pulses, and after a certain number of laser pulses the morphology of the thin film has changed so much that the effect of additional laser pulses becomes insignificant due to local thicknesses of the thin film deviating from the optimal thickness d_{PF} fulfilling the conditions of Fabry Perot resonance. Thus, the process of self-organization of the thin film material converges towards a final nanostructure morphology.

[0117] By adjusting laser parameters such as pulse energy, pulse duration, pulsing frequency, and the number of pulses striking the thin film 1 at the processing area 5, it is possible to produce nanostructures exhibiting different morphologies, and by associating these laser parameters with the obtained nanostructures, it is possible to generate a library of thin film nanostructures for a wide range of laser parameters as well as thin film and substrate materials. Thereby, if at a later stage, specific nanostructures are desired, a look up in the library may help to establish which parameters are to be used in order to obtain such nanostructures.

[0118] Generating a library of nanostructures is particularly advantageous in that it becomes possible to produce a nanostructures product, comprising a restructured thin film 1 and a substrate 2, which utilizes specific nanostructures, without having to guess which laser parameters and materials that are needed to achieve such nanostructures.

[0119] By careful choice of laser parameters, as well as careful selection of substrate and thin film material/thickness, it is possible to obtain nanostructures on a substrate, exhibiting beneficial optical effects. For example, by modifying the morphology of a

thin film 1, supported by a substrate 2, it is possible to create a micro-lens, which is a small lens having a diameter which is generally below 1 mm. An example of such a micro-lens is a Fresnel lens (also shown in figs. 7a-c). Single micro-lenses may for example be used to couple light to optical fibers, while larger arrays containing multiple micro-lenses formed in a one-dimensional or a two-dimensional array on a supporting substrate may be used to increase the light collection efficiency of CCD arrays.

[0120] Figs. 2a-b show embodiments of the invention where a thin film 1 has already undergone a restructuring through self-organization to provide nanostructures 6, and these nanostructures 6 undergoes a further self-organization process using a second narrow-band light source 3a such that modified nanostructures are obtained.

[0121] Fig. 2a shows a thin film 1 on a substrate 2. The thin film 1 have already undergone an irradiation process as described in relation to figs. 1a-d. For the purpose of illustration, the thin film 1, about to be subjected to further irradiation, is the final thin film which has already undergone an irradiation process to produce nanostructures 6 as shown in fig. 1d, although other self-organized films exhibiting different nanostructures 6, resulting from a previous irradiation process, may naturally be used.

[0122] Fig. 2b shows the result of irradiation using the different narrow-band light source 3a. The use of a second narrow-band light source 3a, having a central wavelength different from the central wavelength of the narrow-band light source 3 used in the previous irradiation, results in further self-organization of the nanostructures 6, since the wavelength of the second narrow-band light source 3a may effectively couple to a Fabry Perot resonance supported by the nanostructures obtained by the first irradiation.

[0123] Figs. 3a-b show embodiments of the invention. The drawings illustrate two types of thin films which may be provided before a first irradiation with a narrow-band light source 3 is performed.

[0124] The drawing of fig. 3a illustrates a pristine thin film 1 on a substrate 2. By a pristine thin film, it is understood a thin film where the morphology of the thin film is left unchanged after the deposition of the thin film 1 on the substrate.

[0125] The drawing of fig. 3b illustrates a thin film 1 which has undergone a pre-treatment as depicted by a thin film surface featuring bumps and creases. The pre-treated thin film 1 of fig. 3b is not necessarily depicted to resemble an actual pre-treated thin film, and certain pre-treatments may not impart such extensive structural changes to the thin film. As an example, a pre-treatment may constitute a cleaning of the thin film or a smoothening of the thin film. Alternatively, a pre-treatment may be a treatment which performs a texturing of the thin film surface. Such pre-treatments may utilize chemical methods.

[0126] Fig. 4 shows an embodiment of the invention. The drawing shows how the refractive index n of the system comprising the thin film 1 and substrate 2 changes when going from air/vacuum, i.e. the surrounding medium, through the thin film and into the substrate. The refractive indexes n, shown in the figure, are for the particular center wavelength of the light from the narrow-band light source. As seen, the refractive index of air, or vacuum, is approximately 1, the refractive index of the thin film is approximately 4, and the refractive index of the substrate is approximately 1.5. Thus, a difference Δn in refractive index of about 2.5 exists between the thin film 1 and the substrate 2. Similarly, a large difference in refractive index exists between air/vacuum and thin film. Because of the differences in refractive index at the interface I_{AT} between air/vacuum and thin film 1 and at the interface I_{TS} between the thin film 1 and the substrate 2, the interfaces I_{AT} and I_{TS} effectively functions as mirrors capable of reflecting the light from the narrow-band light source internally in the thin film 1.

[0127] Fig. 5 shows refractive indexes of selected materials. The drawing shows how the refractive index n for silicon, Si, germanium, Ge, indium phosphide, InP, gallium nitride, GaN, and glass depends on wavelength. Si, Ge, InP and GaN represent examples of film materials and glass represent an example of a substrate material. As seen in the figure, the refractive index n for glass is substantially constant in a range from about 350 nm to 800 nm whereas materials like Si, Ge, and InP have refractive

indexes that vary substantially with changing wavelength. The drawing clearly shows a large difference of about 2.5 in refractive index between Si and glass at a specific wavelength of 532 nm, which may represent the central wavelength of light emitted from a narrow-band light source such as a frequency doubled Nd:YAG laser.

[0128] Figs. 6a-c shows embodiments of the invention.

[0129] The drawing of fig. 6a illustrates a thin film, or at least a section of such a thin film. As the light beam 4 of the narrow-band light source 3 impinges the thin film 1 at the processing area 5, the light is resonantly absorbed by the thin film 1 such that the restructuring of the thin film through self-organization of the thin film material is promoted. As the thin film 1 on fig. 6a is illustrated as having a constant thin film thickness across the length of the thin film, the effectiveness of the resonance absorption E_{abs} is constant across the processing area 5. For the purpose of demonstration, the effectiveness of the resonant absorption E_{abs} is 1 (in arbitrary units) across the processing area.

[0130] The drawing of fig. 6b illustrates the thin film 1 from fig. 6a close to the end of the time period in which irradiation of the thin film 1 occurs at the processing area 5. As seen, the morphology of the thin film has changed, and so has the local thicknesses of the thin film within the processing area 5. Since the local thicknesses of the thin film deviates from the theoretically optimal thickness d_{PF} fulfilling the conditions for Fabry Perot resonant absorption, the effectiveness of the resonant absorption E_{abs} is decreased. As seen in the example, the nanostructures 6 have heights, or thicknesses, which are closer to the thin film thickness of the pristine thin film 1 than the valleys existing between the nanostructures 6. Therefore, the positions on the thin film where the nanostructures are present are more susceptible to absorption of light than the positions where the valleys are present. However, the thicknesses at the nanostructures 6 still deviates from the thickness of the pristine thin film 1, and therefore the effectiveness of the resonant absorption is reduced. In fig. 6b, the nanostructures have almost converged at a final morphology, where the effect of further irradiation becomes negligible.

[0131] The drawing of fig. 6c illustrates the final nanostructures 6 of the restructured thin film 1, after the morphology of the thin film has converged to the point where no further changes occur due to a low or non-existing resonant absorption efficiency.

[0132] Figs. 7a-d shows embodiment of the invention.

[0133] The drawing of fig. 7a illustrates an example of a product which may be realized by the method of self-organization of nanostructures 6 as described in the various embodiments of the invention. The product is a Fresnel lens which typically comprises a set of concentric curved surfaces, as illustrated by the circles of increasing radius. The set of concentric curved surfaces may focus light. Fig. 7b illustrates the same Fresnel lens of fig. 7a seen from the side. The arrows indicate paths of light, and it is shown how the different light paths converges at a focal point.

[0134] Fig. 7c show an actual SEM-image of a section of a Fresnel-lens realized by the method of the present invention. The SEM-image shows a top-view of a restructured thin film where a plurality of nanostructures 6 is arranged in such a way that they together form a plurality of centered circles which together are capable in focusing incident light. In this case, the nanostructures are disposed on top of a glass substrate 2, such that incident light may propagate through the glass substrate. In this sense, the nanostructures and glass substrate 2 acts as a focusing lens. Fig. 7d shows a zoom in on the small dashed area in fig. 7.c which shows gradient surface morphologies, of nanostructures 6 which can bend light and cause the focusing effect.

[0135] Fig. 8 shows an embodiment of the invention. The drawing shows an actual SEM-image of another product which may be realized by the method of self-organization of nanostructures as described in the various embodiments of the invention. The product comprises a plurality of nanostructures 6 disposed on top of a substrate. The plurality of nanostructures 6 are arranged in such a way as to approximate a portrait of Mona Lisa.

[0136] List of reference signs:

1	Film
2	Substrate
3, 3a	Narrow-band light source
4	Light beam
5	Processing area
6	Nanostructures
7	Radial line in a reciprocal space
d_T	Film thickness
d_S	Substrate thickness
I_{AT}	Interface between air/vacuum and film
I_{TS}	Interface between film and substrate
n	Refractive index
Δn	Difference in refractive index between film and substrate
E_{abs}	Efficiency of resonant absorption

Claims

1. A method for self-organization of nanostructures, comprising the steps of:

providing a narrow-band light source (3) having a center wavelength;

providing a film (1) on a substrate (2), said film (1) having a film thickness (d_T), said film thickness (d_T) being in the range from 0.9 to 1.1 times a Fabry Perot resonance condition thickness for said center wavelength; and

irradiating said film (1), the irradiating process comprises using said narrow-band light source (3) to induce self-organization of said film (1), thereby obtaining nanostructures (6).

2. The method according to claim 1 wherein said step of providing said film (1) comprises a step selected from the group consisting of PVD-step, CVD-step, ALD-step, PLD-step, spin-coating step, thermal deposition step and combinations thereof.

3. The method according to claim 1 or 2 wherein the method comprises a further step of irradiating said nanostructures (6) using a second narrow-band light source (3a) having a second center wavelength to induce further self-organization of said nanostructures (6).

4. The method according to any of the preceding claims wherein said method comprises a step of measuring said film thickness (d_T) prior to irradiating said film (1) using said narrow-band light source.

5. The method according to any of the preceding claims wherein said film (1) is obtained by pre-treating a precursor film.

6. The method according to any of the preceding claims wherein said pre-treating comprises subjecting said precursor film to a chemical treatment, such as chemical etching.

7. The method according to any of the preceding claims wherein said thickness of said film (1) is below 1000 nm, such as below 600 nm, such as below 300 nm.

8. The method according to any of the preceding claims wherein said film (1) is selected from the group of materials consisting of metals, alloys, semiconductors such as titanium dioxide, or any combination thereof.

9. The method according to any of the preceding claims wherein said film (1) has a refractive index of at least 2, such as at least 2.5.

10. The method according to any of the preceding claims wherein said substrate (2) has a refractive index being at least 0.3 lower than said refractive index of said film (1), such as at least 0.5 lower than said refractive index of said film (1), such as at least 1 lower than said refractive index of said film (1).

11. The method according to any of the preceding claims wherein said narrow-band light source (3) comprises a laser.

12. The method according to any of the preceding claims wherein said narrow-band light source (3) is a pulsed light source.

13. The method according to any of the preceding claims wherein individual pulses of said pulsed narrow-band light source (3) has a pulse energy in the range 1 nJ to 100 μJ.

14. The method according to any of the preceding claims wherein said narrow-band light source (3) has a center wavelength in the range of 200 nm to 20 μm.

15. A product comprising a substrate (2) and nanostructures (6) produced by the method according to any of the claims 1 to 14.

16. A product comprising a substrate (2) and nanostructures (6), the nanostructures (6) being characterized by showing a peak with a width of between 0.1 and 4.0 μm^{-1} of an intensity curve along a radial line in a reciprocal space representation of a SEM image of said product.

17. The product according to claim 16, wherein the nanostructures comprise at least one selected from the list consisting of gold, silver, aluminum, semiconductor material such as titanium dioxide, and combinations thereof.

18. The product according to claim 16 or 17, wherein the material induces a phase shift in 160-200 degrees for normal incident light having said center wavelength.

19. The product according to any of claims 16-18, wherein the nanostructures (6) are characterized by showing a peak with a width of between 0.2 and 2.0 μm^{-1} of an intensity curve along a radial line in a reciprocal space representation of a SEM image of said product, such as 0.3 and 1.0 μm^{-1}.

20. The product according to any of claims 16-19, wherein the product is produced by the method according to any of the claims 1 to 14.

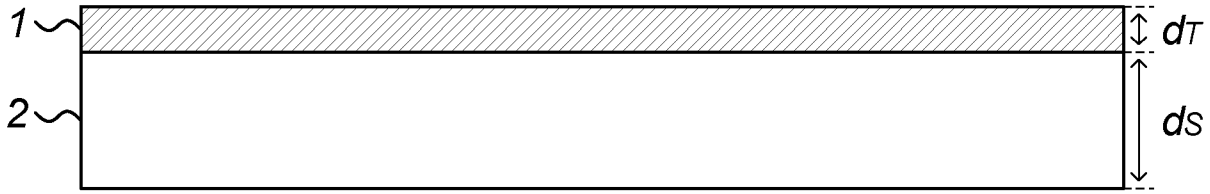

Fig. 1a

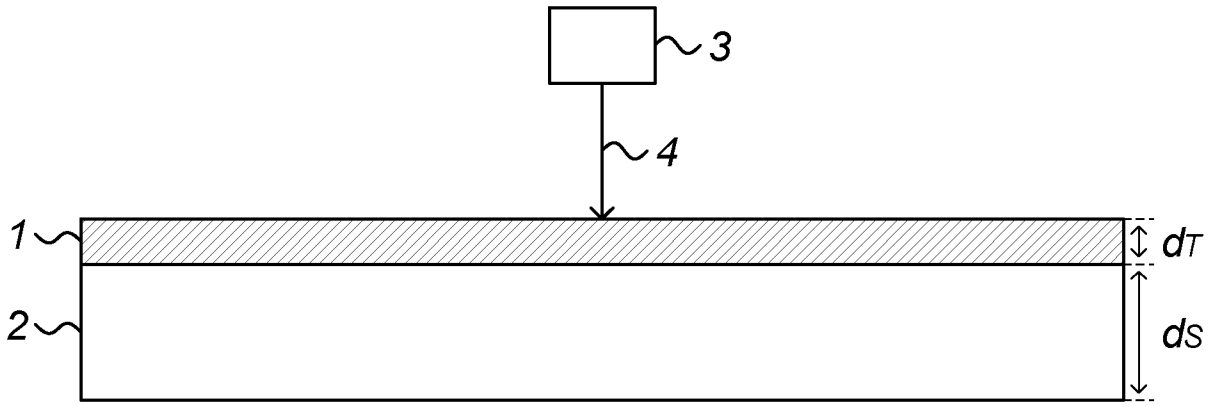

Fig. 1b

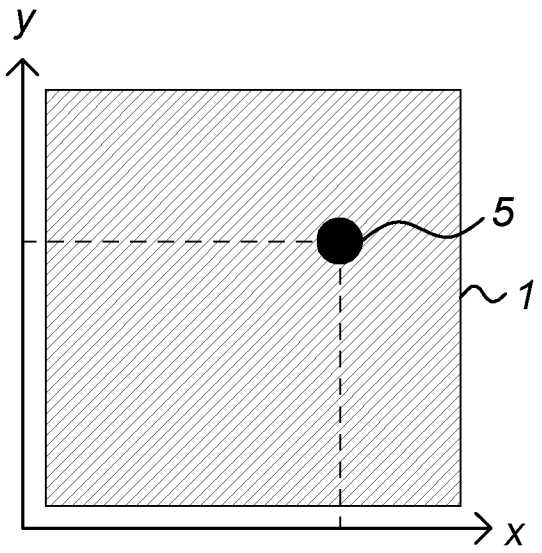

Fig. 1c

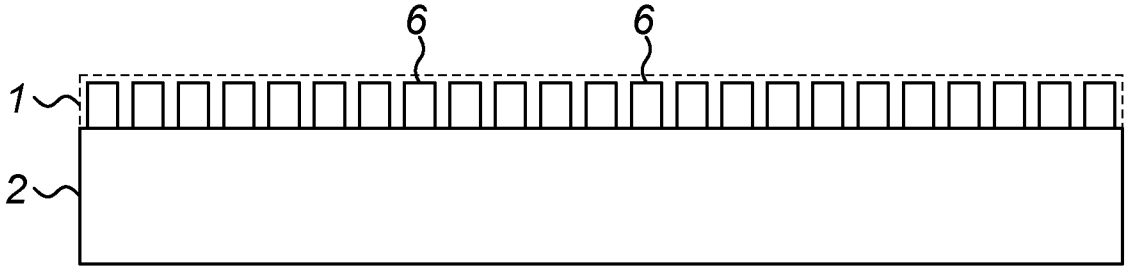

Fig. 1d

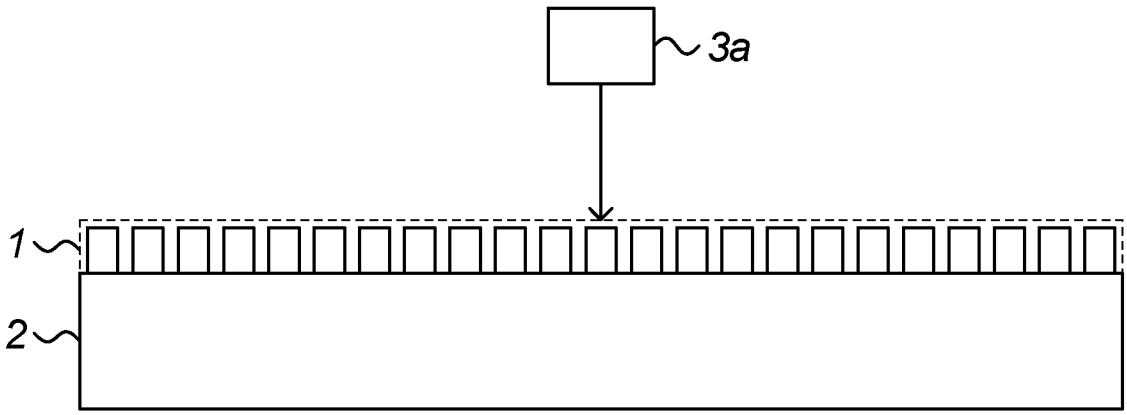

Fig. 2a

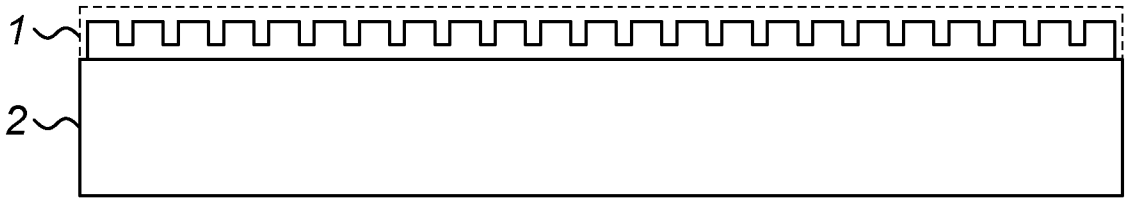

Fig. 2b

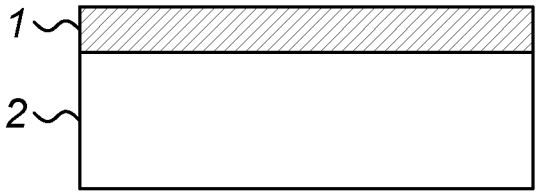

Fig. 3a

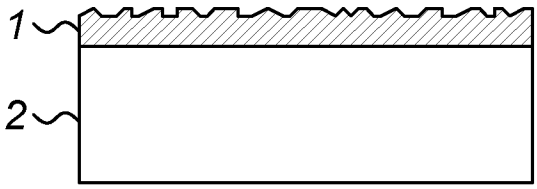

Fig. 3b

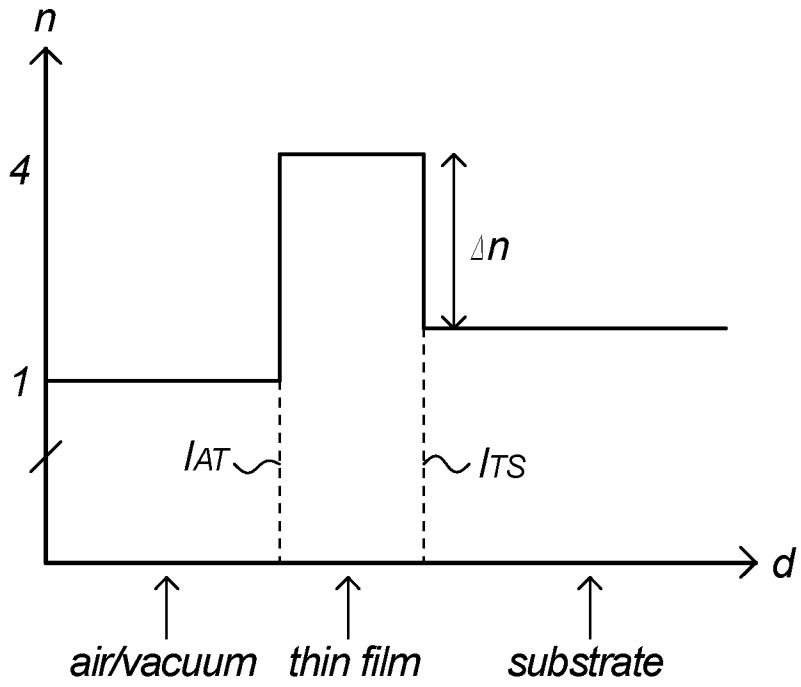
n
4
1
Δn
IAT
ITS
d
air/vacuum
thin film
substrate

Fig. 4

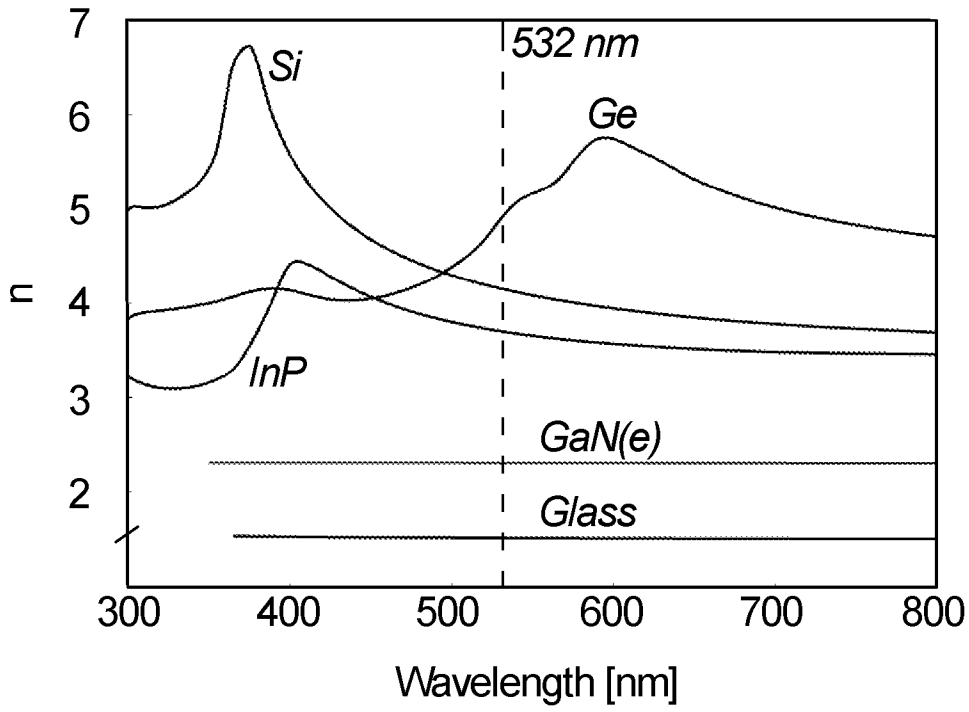
7
6
5
4
3
2
n
532 nm
Si
Ge
InP
GaN(e)
Glass
300
400
500
600
700
800
Wavelength [nm]

Fig. 5

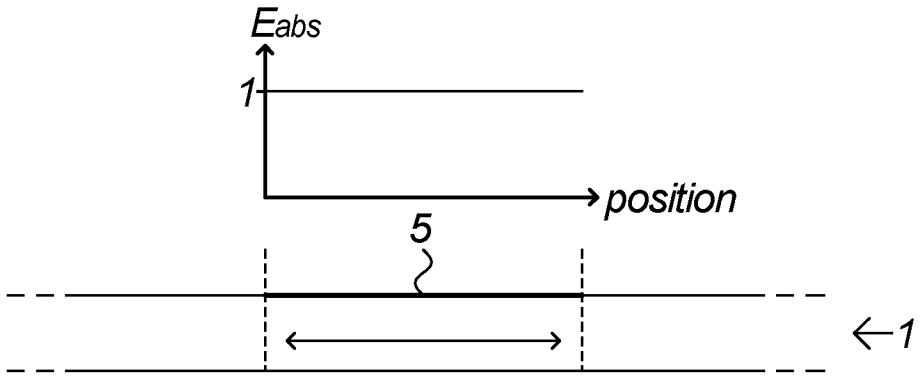

Fig. 6a

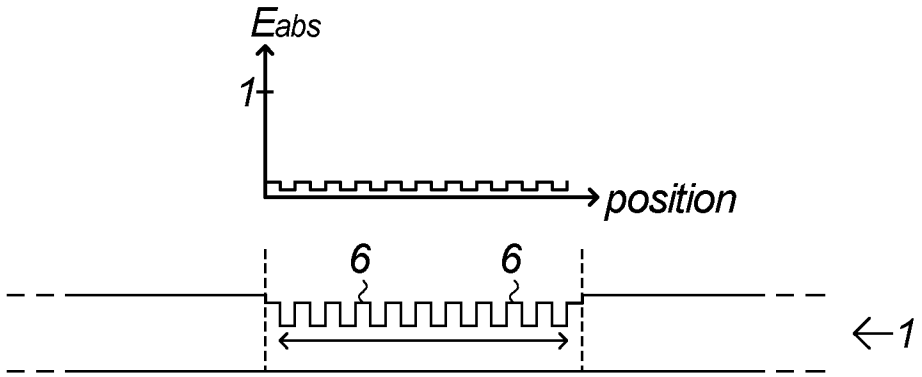

Fig. 6b

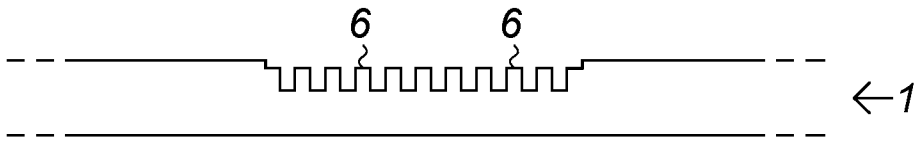

Fig. 6c

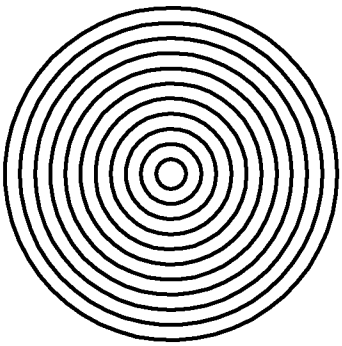

Fig. 7a

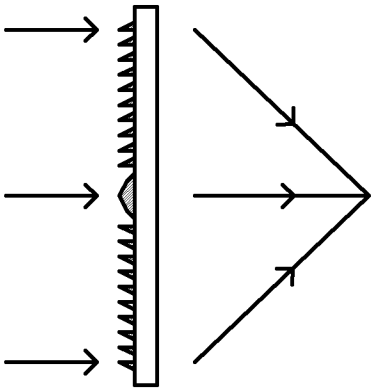

Fig. 7b

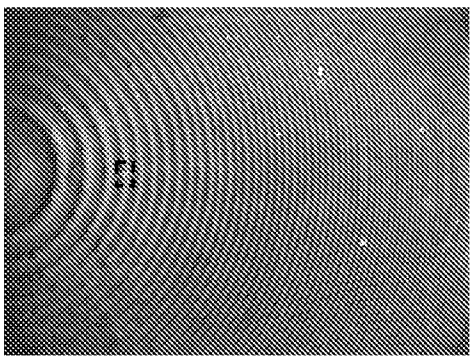

Fig. 7c

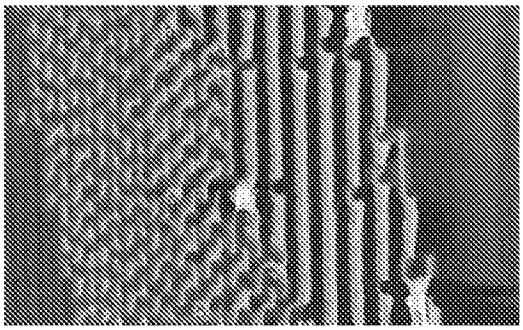

Fig. 7d

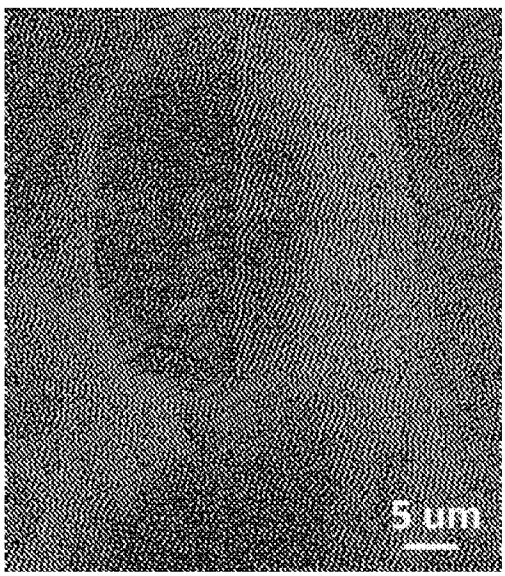

Fig. 8

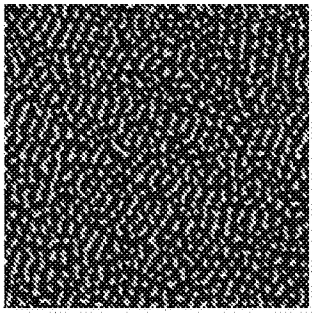

Fig. 9E

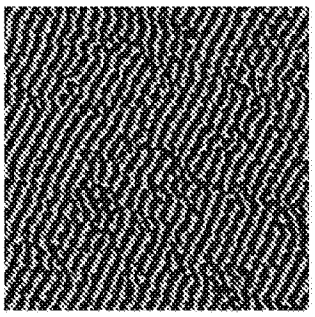

Fig. 9D

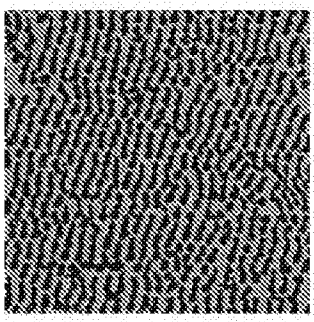

Fig. 9C

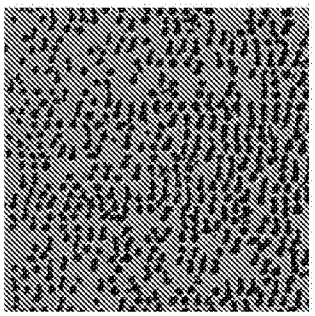

Fig. 9B

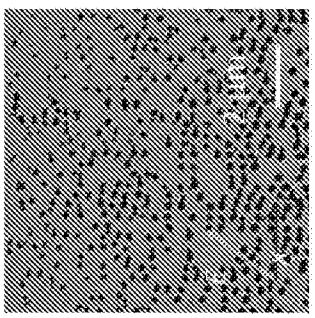

Fig. 9A

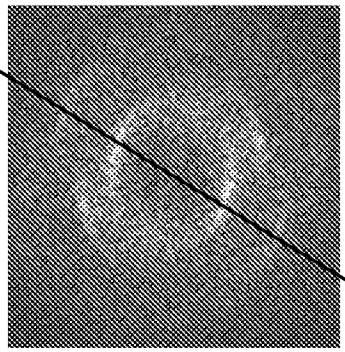

Fig. 10E

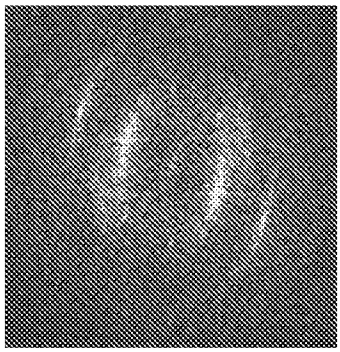

Fig. 10D

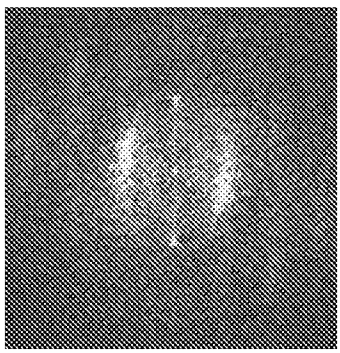

Fig. 10C

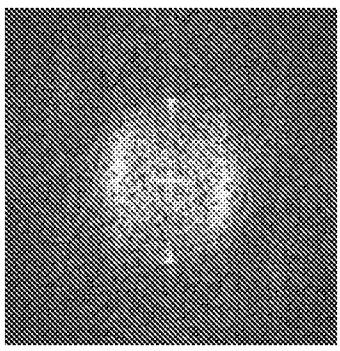

Fig. 10B

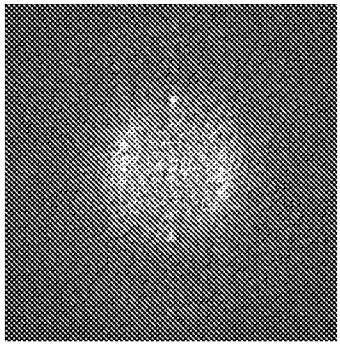

Fig. 10A

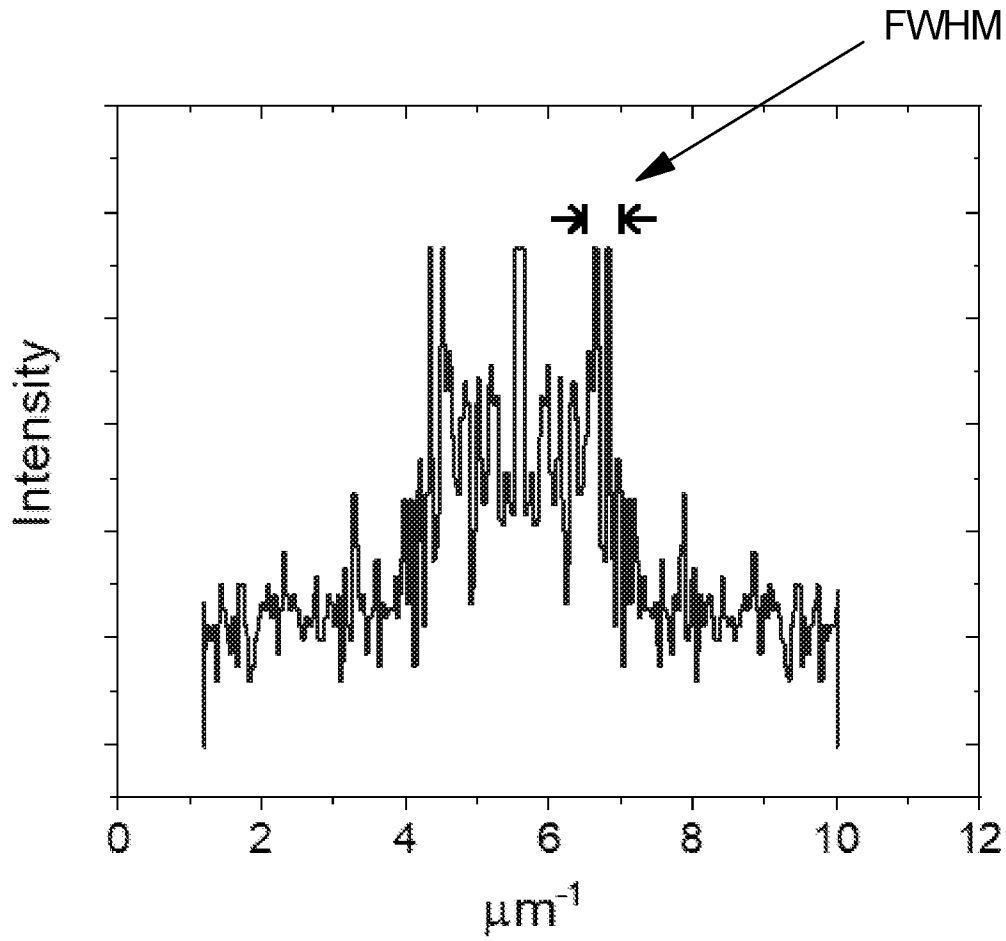

Fig. 11

INTERNATIONAL SEARCH REPORT

International application No
PCT/DK2020/050167

A. CLASSIFICATION OF SUBJECT MATTER
INV. C23C14/58 G03F7/00
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
C23C G03F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	S. YADAVALI ET AL: "Fabricating Metal Nanostructures with Pulsed Laser Dewetting Self-Assembly", ADVANCED MATERIALS & PROCESSES, vol. 171, no. 7, 1 July 2013 (2013-07-01), pages 22-26, XP055643451, cited in the application	15-20
A	figures 2-4	1-14

X	JASON D. FOWLKES ET AL: "Self-Assembly versus Directed Assembly of Nanoparticles via Pulsed Laser Induced Dewetting of Patterned Metal Films", NANO LETTERS, vol. 11, no. 6, 8 June 2011 (2011-06-08), pages 2478-2485, XP055643455, US ISSN: 1530-6984, DOI: 10.1021/nl200921c	15-20
A	figures 2-4	1-14

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
3 September 2020	14/09/2020

Name and mailing address of the ISA/	Authorized officer
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