

APPARATUS AND METHOD FOR PATTERNING A NANOSTRUCTURE IN A TARGET MATERIAL

TECHNICAL FIELD

5

The present disclosure relates to a method of, and apparatus for, patterning a nanostructure in a target material such as silicon. For example, the method and apparatus may be used to pattern nanostructures of semiconductor devices.

BACKGROUND

10

High-throughput fabrication techniques for generating structures with nanoscale features are desirable across a broad range of applications.

15

Traditionally, large-area nanostructures for forming electronic and optical devices have been patterned using photolithography. Various techniques have been used to improve the resolution of conventional photolithography, including light polarization tuning, microsphere-assisted fabrication, and soft lithography. However, due to the optical diffraction limit, fabrication of smaller features requires ultraviolet or even extreme UV light sources, thus necessitating a clean room environment. It is thus extremely challenging to make large-area and ~10 nm features at a reasonable cost.

20

Other methods, such as electron beam lithography and reactive ion etching, can reliably achieve ~10 nm resolution, but are expensive and inefficient.

25

Some approaches based on near-field laser fabrication, such as scanning probe microscopy, scanning near-field optical lithography, and plasmonic nanolithography, can overcome the optical diffraction limit and realize fabrication of structures of ~10 nm resolution. However, these techniques have low throughput due to exponential decay of evanescent waves and low scanning speed (<100 $\mu\text{m/s}$), thus limiting their practical application for large-area nanofabrication.

30

Fabrication of ~100 nm structures by femtosecond laser irradiation in the far field is also currently possible. The most widely used method is two-photon polymerization (TPP), which normally can achieve nanostructures with a resolution of ~150 nm. Assisted by stimulated emission depletion, the feature size induced by TPP can be further reduced to ~40 nm.

35

However, the above laser-assisted lithography methods can only be employed in phase change and transparent materials, or require fabrication in liquids.

There remains a need for a method that can produce sub-100 nm features directly on semiconductor surfaces by direct laser patterning in the far field.

SUMMARY

Disclosed herein is an apparatus for patterning a nanostructure in a target material, comprising:

- a pulsed-mode femtosecond laser;
 - a target translation stage for moving the target material to scan pulses from the pulsed-mode femtosecond laser across the target material in a desired pattern;
 - a polarizing beam splitter for splitting a source beam from the pulsed-mode femtosecond laser into a first beam having a first polarization, and a second beam that has a second polarization that is orthogonal to the first polarization; and
 - an optical arrangement for directing the first and second beams towards the target material through an objective lens;
- wherein the optical arrangement is configured such that pulses of the first beam and pulses of the second beam arrive at substantially the same time at the target material.

By simultaneously irradiating the target with dual beams from a pulsed laser, it is possible to pattern sub-100 nm nanostructures on the target material (such as silicon) in the far field, and under atmospheric conditions, via direct laser irradiation.

In some embodiments, the optical arrangement comprises:

- a first mirror positioned to reflect the first beam;
- a second mirror positioned to reflect the second beam;
- a 50:50 beam splitter positioned to transmit the first beam on reflection from the first mirror, and to reflect the second beam on reflection from the second mirror; and
- a third mirror that is positioned to reflect the first beam and the second beam towards the objective lens.

In some embodiments, the second mirror is rotatable to adjust a spatial separation between first points at which the pulses of the first beam impinge on the target material, and second points at which the pulses of the second beam impinge on the target material.

In some embodiments, the apparatus comprises a half-wave plate positioned in a path of the first beam or in a path of the second beam to modulate the fluence of the first beam relative to the second beam. The half-wave plate may be positioned between the first mirror and the 50:50 beam splitter, or between the polarizing beam splitter and the second mirror.

In some embodiments, the apparatus comprises at least one linear translation stage for adjusting an optical path length difference between the first beam and the second beam. For example, each component of the optical arrangement may be mounted to a linear translation stage.

Some embodiments of the apparatus comprises a second half-wave plate positioned in a path of the source beam to modulate the fluence of the source beam. The second half-wave plate may be positioned between the laser and the polarizing beam splitter.

In some embodiments, the second mirror is positioned at an angle to produce a spatial separation of less than about 0.5 microns between respective first points and second points.

Also disclosed herein is a method for patterning a nanostructure in a target material, comprising:

- splitting a source beam from a pulsed-mode femtosecond laser into a first beam having a first polarization and a second beam having a second polarization that is orthogonal to the first polarization;
- directing the first and second beams towards the target material through an objective lens such that pulses of the first beam and pulses of the second beam arrive at substantially the same time at the target material; and
- scanning the pulses of the first beam and the pulses of the second beam across the target material in a desired pattern.

In some embodiments the method comprises:

- reflecting the first beam towards a 50:50 beam splitter such that the first beam is transmitted through the 50:50 beam splitter;
- reflecting the second beam towards the 50:50 beam splitter such that the second beam is reflected from the 50:50 beam splitter; and
- reflecting the first beam and the second beam towards the objective lens.

Some embodiments of the method comprise adjusting a spatial separation between first points at which the pulses of the first beam impinge on the target material, and second points at which the pulses of the second beam impinge on the target material, by rotation of a mirror that reflects the second beam towards the 50:50 beam splitter.

5

Some embodiments of the method comprise modulating the fluence of the first beam relative to the second beam using a half-wave plate.

The method may comprise adjusting an optical path length difference between the first beam and the second beam by at least one linear translation stage.

10

In some embodiments the method comprises modulating the fluence of the source beam using a second half-wave plate.

In some embodiments of the method, the spatial separation between respective first points and second points is less than about 0.5 microns.

15

BRIEF DESCRIPTION OF THE DRAWINGS

Some embodiments of a system and method for patterning a nanostructure in a target material will now be described, by way of non-limiting example only, with reference to the accompanying drawings in which:

20

Figure 1 is an optical system diagram of an example apparatus for patterning a nanostructure in a target material;

25

Figure 2 shows SEM and AFM images of nanostructures induced by spatial double femtosecond laser beams;

Figure 3 shows SEM images of nanostructures induced by spatial double femtosecond laser beams at different gaps and laser fluences;

Figure 4 shows model calculations of intensity distributions of dual femtosecond laser beams having varying degrees of overlap;

30

Figure 5 is a schematic diagram of a volume element of a silicon target during laser irradiation;

Figure 6 shows (a) SEM images for a curve nanostructure fabricated using orthogonally polarized double femtosecond laser beams, (b) an SEM image of a curve nanostructure fabricated using orthogonally polarized double femtosecond laser beams that are at an angle to the scanning direction; and a schematic depiction of a model for generation of

35

nanostructures for (c) horizontal polarization; (d) vertical polarization; and (e) two overlapping orthogonal polarizations; and

Figure 7 is a flow diagram of an example method of patterning a nanostructure in a target material.

5

DETAILED DESCRIPTION

Embodiments of the present disclosure enable fabrication of sub-100 nm features directly in the far field, in ambient air, in a target material (such as silicon) via orthogonally polarized and overlapping femtosecond laser double-pulse trains. The laser fluence, gap
10 between the pulses, and polarization can be controlled by the optical path length difference and the use of half-wavelength plates via a beam splitting system. Embodiments can achieve a feature resolution fabricated on silicon of around ~15 nm. In addition, the formation of the nanostructures can be controlled in parallel to the scanning direction, regardless of the scanning path.

15 Embodiments may find application in a wide variety of fields that require nanofabrication. For example, embodiments may be used to fabricate nanochips used in computing devices such as mobile phones and laptop computers, or electronic systems of automobiles. In some embodiments the technology may be used to replace or supplement traditional lithography techniques used in the semiconductor industry.

20 Figure 1 shows one example configuration of an apparatus 10 for patterning a nanostructure in a surface of a target material 24. The apparatus 10 comprises a pulsed-mode femtosecond laser 12 that produces a source beam 13 that passes through an optical arrangement, generally indicated at 16, for irradiating the target material 24. The target material 24 is mounted to a target translation stage 22 that is operable to move the target
25 material 24 such that pulses from the pulsed-mode femtosecond laser 12 can be scanned across the target material 24 in a desired pattern, for example to form a semiconductor device or part thereof. The target translation stage 22 may be a 3D XYZ translation stage.

The example apparatus 10 comprises a polarizing beam splitter 14 that is arranged to split the source beam 13 into a first beam 18 having a first polarization, the path of which is
30 indicated by dotted lines; and a second beam 20 having a second polarization that is orthogonal to the first polarization, the path of the second beam 20 being indicated by solid lines.

The optical arrangement 16 is configured to direct the first and second beams 18 and 20 towards the target material 24 through an objective lens 26, and is further configured
35 such that pulses of the first beam 18 and pulses of the second beam 20 arrive at substantially the same time at the target material 24. Accordingly, the optical arrangement

16 enables simultaneous irradiation of the target material 24 by two pulse trains of orthogonal polarizations. This can result in nanoscale structures of different types depending on the spatial separation between the pulse trains at the target material 24 and the fluence of the laser 12, as will be described in further detail below.

- 5 Simultaneity of arrival of the pulse trains at the target material 24 can be achieved by the use of a linear translation stage 22 to precisely control the delays of the first and second beams 18, 20. The translation stage 22 can be used to adjust the delay individually in each arm of the optical arrangement 16.

10 In some embodiments, the optical arrangement 16 comprises a first mirror 36 that is positioned to reflect the first beam 18 towards a 50:50 beam splitter 40. A second half-wave plate 38 may be positioned between the first beam 18 and the 50:50 beam splitter 40. The optical arrangement 16 also comprises a second mirror 42 that is positioned to reflect the second beam 20 towards the 50:50 beam splitter 40. The first and second beams 18 and 20 are recombined at the 50:50 beam splitter 40, which transmits the first beam 18 on reflection from the first mirror 36, and reflects the second beam 20 on reflection from the second mirror 42. The recombined first and second beams 18, 20 then propagate towards a third mirror 44 of the optical arrangement 16. The third mirror 44 is positioned to reflect the first beam 18 and the second beam 20 towards the objective lens 26, which focuses the beams 18, 20 onto the target 24.

20

The second mirror 42 is rotatable. This enables the spatial separation between beams 18 and 20 at the target material 24 to be adjusted.

25 In some embodiments, the apparatus 10 may comprise a shutter 30 located in front of a first half-wave plate 32 to achieve a desired number of pulses irradiating the target material 24. The switch time of the shutter 30 may be tuned to control the number of pulses. The first half-wave plate 32 enables tuning of the fluence of laser 12. The apparatus 10 may also comprise an isolator 34 that prevents laser 12 from being damaged by strong reflections from the target 24.

- 30 The apparatus 10 further comprises a controller 28, such as a computer system that has suitable interfacing hardware and/or software components for control of laser 12, target translation stage 22, and rotatable mirror 42.

The controller 28 may be configured to control the fluence of laser 12 and/or the spatial separation between the respective pulse trains of the first beam 18 and second beam 20 (by suitable rotation of second mirror 42) to affect the type of nanostructure that is patterned on the target material 24.

35

For example, as shown in Figure 2, a number of nanostructured lines along the scan direction can be controlled in accordance with the laser fluence and spacing between the first and second beams 18 and 20. Figures 2(a) to 2(d) show SEM images of the surface of target material 24 for four different combinations of laser fluence and beam separation.

- 5 Figures 2(e) to 2(h) show the corresponding AFM images and surface profiles for the different respective combinations of fluence and beam separation. It can be seen that the full widths at half maximum (FWHMs) of the structures are mostly smaller than 30 nm.

As shown in Figure 2(a) and Figure 2(e), in the case of 1.6 J/cm^2 laser fluence and $\sim 0 \text{ }\mu\text{m}$ beam gap, a nanostructure of $\sim 22 \text{ nm}$ FWHM forms on a sub-micron bump. Since the multiple pulse ($\sim 3.8 \times 10^4$ pulses) irradiation results in a considerable thermal effect, the raised part observed in the atomic force microscopy (AFM) image is due to the melting layer induced by the temperature gradient during the laser irradiation. A laser fluence of 1.6 J/cm^2 is above the ablation threshold of the target material 24, which in the illustrated example is silicon.

- 10 Figures 2(b) and 2(f) show that at a fluence of 1.6 J/cm^2 and a $\sim 0.5 \text{ }\mu\text{m}$ gap between the two laser beams 18 and 20, there are two nanostructures of $\sim 30 \text{ nm}$ FWHM generated on the sub-micron bump. At a laser fluence of 1.6 J/cm^2 , the number of nano-lines changes from 1 to 2 as the gap changes from ~ 0 to $\sim 0.5 \text{ }\mu\text{m}$. At this separation with the beams 18 and 20 in partial overlap, there are two energy peaks (as will be explained later with reference to Figure 4), with each peak being near the material ablation threshold. Thus, introducing a spatial separation between the two beams can result in the generation of a double-line nanostructure instead of a single-line nanostructure.

If the laser fluence is further increased beyond the ablation threshold (still with a gap of $0.5 \text{ }\mu\text{m}$ between the beams), for example to 1.8 J/cm^2 or 2 J/cm^2 , triple-line and four-line structures can be created, as shown in Figures 2(c) and 2(g) and Figures 2(d) and 2(h), respectively. At 2 J/cm^2 , the FWHM of the nanostructures can be reduced to 12 nm ($\lambda/66$). Thus, at a gap of $0.5 \text{ }\mu\text{m}$, the number of nano-lines can be increased from 2 to 4 as the laser fluence increases from 1.6 J/cm^2 to 2.0 J/cm^2 , and the period of the nanoline structures reduces from ~ 400 to 150 nm . With increasing laser fluence, more nano-lines can be generated inside the area of overlap between the beams.

- 25 Depending on the energy distribution (e.g. as shown in Figure 4), the increase of laser fluence may result in more regions of the area of overlap reaching the melting threshold of the target material, which can generate more nano-lines in the area of overlap. Since the overlap area remains constant at $\sim 0.5 \text{ }\mu\text{m}$, more nano-lines means smaller periods.
- 35 Furthermore, the width and depth increase as laser fluence increases. Thus, when the

scanning speed and gap remain constant, the increase of laser fluence can reduce the period and enlarge the width and depth of the nano-line structures.

Figure 3(a) shows further examples of SEM images of nanostructures generated at a laser fluence of 1.6 J/cm² (i.e., above the ablation threshold of the target material 24) by the two femtosecond laser beams 18 and 20, at a scanning speed of 2 mm/s, for various gaps from 4 μm to 0.

It will be appreciated that the scanning speed may be adjusted to produce a desired number of pulses for irradiating the target material. In particular, a higher scanning speed means that fewer pulses will impinge on a given area of the target. The laser fluence may also be tuned such that smaller nanostructures are produced. The present inventors have found that for a laser repetition rate of 78 MHz, a scanning speed of 5 mm/s is optimal.

In another example, the controller 28 may be configured to set the laser fluence above the melting threshold (1.2 J/cm² for silicon), but below the ablation threshold, of the target material 24. SEM images of example nanostructures that can be fabricated under this condition are shown in Figure 3(b). As the gap reduces from 4 μm to 0.5 μm, the surface structure varies from periodic ripple structures (>2 μm gap) to grid structures (0.5 and 1 μm gaps) in the overlap area. As the gap approaches ~0 μm, periodic ripple structures parallel to the scanning direction are created.

Turning now to Figures 4 to 6, certain additional principles underpinning embodiments of the present disclosure will be described.

Intensity distributions of overlapping beams

For two laser beams 18, 20 having orthogonal polarizations and zero time delay with respect to each other, the distribution of the electric field E_0 in different areas can be expressed as:

$$\vec{E}_0 = \begin{cases} \vec{E}_1(\vec{r}) + \vec{E}_2(\vec{r}) & \text{overlapping area} \\ \frac{\vec{E}_1(\vec{r})}{E_2(\vec{r})} & \text{non - overlapping area} \\ E_0 \hat{x} e^{\left(\frac{-r^2}{\omega_0^2}\right)} & \text{non - overlapping area} \\ E_0 \hat{y} e^{\left(\frac{-(\vec{r}-\vec{\mu})^2}{\omega_0^2}\right)} & \text{non - overlapping area} \end{cases} \quad (1)$$

25

where $\vec{r}$ and $\vec{\mu}$ are the radial distances from the center axes of the first beam 18 and the second beam 20, respectively. ω_0 (which may be 1 μm for example) is the radius of the Gaussian beam. $E_0 = 1$ is the normalized electric field intensity. Thus, the intensity in the overlapping and non-overlapping areas for different gaps can be calculated by Equation (1). The calculation results are shown in Figure 3, which demonstrates that the

30

energy of each spot's center area is always higher than in the overlapping area, when the gap is larger than 0.5 μm . Then the intensity in the overlapping area keeps increasing as the gap reduces from 0.5 μm to 0 μm . Only at zero gap do the FWHMs for the single beam and two beam irradiation become equal.

5 Laser induced melting and pressure change

Referring to Figure 5 and considering the target material 24 as being composed of a plurality of volume elements (voxels), a heated voxel of the target material 24 is confined by cold non-irradiated material and a pressure increase is generated inside the voxel. The increase in pressure assists in closure of the line of irradiation, as indicated.

- 10 A further influence on the nanoline formation process is the increase in absorption coefficient of the target material with temperature. For a silicon target, an increase in temperature to 1200 °C increases the absorption coefficient from ~ 0.075 to ~ 0.25 at a wavelength of 800 nm. Further, the absorption coefficient of amorphous silicon ($\alpha\text{-Si}$) at 1200 °C is 1.25, which is over 20 times compared to that at room temperature (~ 0.05).
- 15 After multiple laser irradiation, the silicon surface may transition to an amorphous and molten phase. In this case, the absorption coefficient in the irradiated area will increase significantly due to the high temperature, which also means the absorption of the laser in the irradiated area is enhanced. Thus, with an increase in the number of laser pulses striking the irradiated area, the laser induced surface modification should be stronger.

20 The lattice constant difference between liquid and solid silicon

Normally, the lattice constant in the liquid and solid phases is different. The lattice of silicon at 300 K is about 5.43 Å, while it is nearly 5.46 Å at a temperature of 1500 K. Since the molten temperature of silicon is 1687 K, the lattice constant difference between liquid and solid silicon should be over 0.03 Å. Thus, the percentage of difference is nearly 0.55%.

- 25 The width of the molten region in Figure 2(h) is $\sim 1 \mu\text{m}$. Thus, the plane lattice number of silicon should be $(1 \times 10^6)/5.43 \approx 1.84 \times 10^5$. Since the lattice constant difference is over 0.03 Å between liquid and solid silicon, the total difference due to the transition from liquid and solid is at least: $0.03 \times 1.84 \times 10^5 = 5.52 \times 10^3 \text{ Å} = 5.52 \text{ nm}$.

- Without wishing to be bound by theory, it is thought that this lattice constant difference induced over a 5.5 nm morphology difference may contribute to the formation of the nano-line structure ($\sim 12 \text{ nm}$).
- 30

Incubation effect due to multiple laser irradiation

When the laser fluence of a single pulse is near the melting threshold, incubation may explain the observed decrease in the laser fluence required for laser-induced damage of

materials when irradiated by multiple pulses, in contrast to that for a single pulse. The incubation effect is mostly generated from the multiple pulse irradiation (>1000 pulses) at a high repetition rate (>1 kHz). Physically, the formation of defect states is believed to be responsible for incubation. Such defects provide sub-bandgap levels that serve as easily excitable sources for subsequent electronic excitations. These slight changes in optical property are magnified in the highly nonlinear absorption, leading to macroscopic changes in not only the melting threshold but also the morphology of observed processed regions.

In experiments conducted by the present inventors, the double beam fabrication is processed under low pulse energy (~ 10 nJ) and multiple pulse ($\sim 3.8 \times 10^4$ pulses) irradiation at a high repetition rate (76 MHz), thus the heat accumulation can be controlled to near the melting threshold. Normally, the density of liquid Si ($\rho_l = 2.52 \text{ g/cm}^3$) is slightly different from the density of solid Si ($\rho_s = 2.32 \text{ g/cm}^3$). In this case, except for the center area of laser irradiation, the melting region will be rebuilt due to the surface tension of liquid from the edge to the center. As a consequence, the liquid silicon is squeezed radially to the center and forms a protrusion during the cooling process. The surface tension is determined by the surface tension coefficient and the length of the liquid boundary. As seen in the AFM images of Figure 2, the depth of the molten region is ~ 10 nm, which means the surface tension is very small. Under this small surface tension, a nanostructure of ~ 10 nm width can be formed after the cooling of molten silicon.

Figures 2 and 3 show examples of straight-line nanostructures with scanning direction parallel to one of the polarizations of the beams 18 and 20, as fabricated by methods and apparatus according to certain embodiments. It is also possible to fabricate other types of nanostructure of essentially arbitrary shape.

For example, as shown in Figure 6(a), it is possible to fabricate a nano-curve at FWHM smaller than 100 nm directly on a Si surface regardless of the scanning direction. In the case of oblique lines, as shown in Figure 6(b), triple-line nanostructures are achieved even though the scanning direction is parallel to neither of the two orthogonal polarizations of the first beam 18 and second beam 20. These results indicate that the direction of the nanostructures induced by orthogonally polarized two femtosecond laser beams is polarization-independent.

A simple model is illustrated in Figures 6(c) to 6(e) to qualitatively demonstrate the mechanism behind curve or oblique line formation. The vectors $\vec{\eta}_H$ and $\vec{\eta}_V$ represent the nanostructures induced by two orthogonal polarized laser beams 18 and 20, respectively. The propagation direction for the nanostructures is consistent with the laser polarization direction. η_o represents the maximum amplitude of the nanostructures excited by a single laser beam when the scanning direction is perpendicular to the laser polarization. The

nanostructures excited by orthogonally polarized two femtosecond laser beams can be decomposed along the horizontal and vertical directions, as shown in Figure 6(e). Along the axis parallel to the scanning path, the components of the two laser beams have an equal value but are in the opposite direction to each other. Hence, the nanostructures excited by orthogonally polarized double femtosecond laser beams are oriented perpendicularly to the scanning direction. In this case, nanostructures parallel to the scanning direction can be formed. Furthermore, the amplitude of coupling nanostructures is $|\vec{\eta}| = |\vec{\eta}_H|\cos(\pi/2 - \theta) + |\vec{\eta}_V|\cos(\theta) = \eta_o$. This indicates that the amplitude of the nanostructures excited by the orthogonally polarized femtosecond laser beams 18, 20 remains constant, regardless of the scanning direction. Thus, the patterning of any desired nanostructure having ~10 nm features directly on semiconductor surfaces is feasible by orthogonally polarized double femtosecond laser beam irradiation.

In some embodiments, instead of beams 18 and 20 having a Gaussian distribution, a laser with a flat-topped energy distribution may be used. Under double flat-topped beam irradiation, the energy distribution difference between the overlapping and non-overlapping areas will be more obvious. Accordingly, the micro-scale bumps seen in Figure 2 may be eliminated or reduced significantly.

In some embodiments, the depth of nanostructure can be increased by optimizing the laser parameters. For example, according to the model depicted in Figures 6(c) to 6(e), it is possible to increase the depth of the nanostructure through two beams with nonorthogonal polarizations. To this end, phase shifting means such as the half waveplate 38 may be introduced into one or both arms of the optical arrangement 16 to change the relative polarizations of the first beam 18 and second beam 20.

In some embodiments the beams can be other than linearly polarized. For example, double beams with circular and elliptical polarizations can also be used to achieve ~10 nm nanostructures with different morphologies.

Turning now to Figure 7, an example method 700 of patterning a nanostructure in a surface of a target material will be described.

The method 700 begins at step S1 by splitting a source beam from a pulsed-mode femtosecond laser into a first beam having a first polarization and a second beam having a second polarization that is orthogonal to the first polarization.

Next, at step S2, the first and second beams are directed towards the target material through an objective lens such that pulses of the first beam and pulses of the second beam arrive at substantially the same time at the target material. This may be achieved via an optical arrangement such as the optical arrangement 16 of Figure 1.

At step S3, the pulses of the first beam and the pulses of the second beam are scanned across the target material in a desired pattern to form the nanostructure in the surface of the target material. This may be done by moving a translation stage to which the target material is mounted. The translation stage may be moved at a desired scanning speed, such as a speed between 2 mm/s and 5 mm/s, and in a manner conforming to the desired pattern.

In some embodiments, the method 700 may comprise adjusting a fluence of the source beam and/or a spatial separation between the pulses of the first beam and the pulses of the second beam at the target material. Adjusting the spatial separation causes different intensity distributions to be experienced by the target material (see Figure 4). In some embodiments this may be done during a scan, so that the morphology and/or dimensions of the nanostructures patterned on the target material may vary across the target material. This may be useful when wishing to form regions intended to have different functional characteristics in a single scan, for example.

Many modifications will be apparent to those skilled in the art without departing from the scope of the present invention.

Throughout this specification, unless the context requires otherwise, the word "comprise", and variations such as "comprises" and "comprising", will be understood to imply the inclusion of a stated integer or step or group of integers or steps but not the exclusion of any other integer or step or group of integers or steps.

The reference in this specification to any prior publication (or information derived from it), or to any matter which is known, is not, and should not be taken as an acknowledgment or admission or any form of suggestion that that prior publication (or information derived from it) or known matter forms part of the common general knowledge in the field of endeavour to which this specification relates.

CLAIMS

1. Apparatus for patterning a nanostructure in a target material, comprising:
 - a pulsed-mode femtosecond laser;
 - 5 a target translation stage for moving the target material to scan pulses from the pulsed-mode femtosecond laser across the target material in a desired pattern;
 - a polarizing beam splitter for splitting a source beam from the pulsed-mode femtosecond laser into a first beam having a first polarization, and a
 - 10 second beam that has a second polarization that is orthogonal to the first polarization; and
 - an optical arrangement for directing the first and second beams towards the target material through an objective lens;
 - wherein the optical arrangement is configured such that pulses of the first
 - 15 beam and pulses of the second beam arrive at substantially the same time at the target material.
2. Apparatus according to claim 1, wherein the optical arrangement comprises:
 - a first mirror positioned to reflect the first beam;
 - 20 a second mirror positioned to reflect the second beam;
 - a 50:50 beam splitter positioned to transmit the first beam on reflection from the first mirror, and to reflect the second beam on reflection from the second mirror; and
 - a third mirror that is positioned to reflect the first beam and the second
 - 25 beam towards the objective lens.
3. Apparatus according to any one of the preceding claims, wherein the second mirror is rotatable to adjust a spatial separation between first points at which the pulses of the first beam impinge on the target material, and second points at
- 30 which the pulses of the second beam impinge on the target material.
4. Apparatus according to claim 3, wherein the second mirror is positioned at an angle to produce a spatial separation of less than about 0.5 microns between respective first points and second points.
- 35 5. Apparatus according to any one of the preceding claims, comprising a half-wave plate positioned in a path of the first beam or in a path of the second beam to modulate the fluence of the first beam relative to the second beam.

6. Apparatus according to any one of the preceding claims, comprising at least one linear translation stage for adjusting an optical path length difference between the first beam and the second beam.
- 5
7. Apparatus according to claim 6, wherein each component of the optical arrangement is mounted to a linear translation stage.
8. Apparatus according to any one of the preceding claims, comprising a second half-wave plate positioned in a path of the source beam to modulate the fluence of the source beam.
- 10
9. A method of patterning a nanostructure in a target material, comprising:
- 15
- splitting a source beam from a pulsed-mode femtosecond laser into a first beam having a first polarization and a second beam having a second polarization that is orthogonal to the first polarization;
- directing the first and second beams towards the target material through an objective lens such that pulses of the first beam and pulses of the second beam arrive at substantially the same time at the target material; and
- 20
- scanning the pulses of the first beam and the pulses of the second beam across the target material in a desired pattern.
10. A method according to claim 9, comprising:
- 25
- reflecting the first beam towards a 50:50 beam splitter such that the first beam is transmitted through the 50:50 beam splitter;
- reflecting the second beam towards the 50:50 beam splitter such that the second beam is reflected from the 50:50 beam splitter; and
- reflecting the first beam and the second beam towards the objective lens.
- 30
11. A method according to claim 9 or claim 10, comprising adjusting a spatial separation between first points at which the pulses of the first beam impinge on the target material, and second points at which the pulses of the second beam impinge on the target material, by rotation of a mirror that reflects the second beam towards the 50:50 beam splitter.
- 35
12. A method according to any one of claims 9 to 11, comprising modulating the fluence of the first beam relative to the second beam using a half-wave plate.

13. A method according to any one of claims 9 to 12, comprising adjusting an optical path length difference between the first beam and the second beam by at least one linear translation stage.
- 5 14. A method according to any one of claims 9 to 13, wherein the first and second beams at least partially overlap at the target material.
15. A method according to claim 14, wherein a combined fluence of the first beam and the second beam in an overlap region is above a melting threshold of the target material.
- 10 16. A method according to claim 15, wherein the combined fluence is below an ablation threshold of the target material.
- 15 17. A method according to any one of claims 9 to 16, comprising modulating the fluence of the source beam using a second half-wave plate.
18. A method according to any one of claims 9 to 17, wherein the spatial separation between respective first points and second points is less than about 0.5 microns.
- 20