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The Director

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Therefore, this United States

Patent

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If the application for this patent was filed on or after December 12, 1980, maintenance fees are due three years and six months, seven years and six months, and eleven years and six months after the date of this grant, or within a grace period of six months thereafter upon payment of a surcharge as provided by law. The amount, number and timing of the maintenance fees required may be changed by law or regulation. Unless payment of the applicable maintenance fee is received in the United States Patent and Trademark Office on or before the date the fee is due or within a grace period of six months thereafter, the patent will expire as of the end of such grace period.

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If the application for this patent was filed on or after June 8, 1995, the term of this patent begins on the date on which this patent issues and ends twenty years from the filing date of the application or, if the application contains a specific reference to an earlier filed application or applications under 35 U.S.C. 120, 121, 365(c), or 386(c), twenty years from the filing date of the earliest such application ("the twenty-year term"), subject to the payment of maintenance fees as provided by 35 U.S.C. 41(b), and any extension as provided by 35 U.S.C. 154(b) or 156 or any disclaimer under 35 U.S.C. 253.

If this application was filed prior to June 8, 1995, the term of this patent begins on the date on which this patent issues and ends on the later of seventeen years from the date of the grant of this patent or the twenty-year term set forth above for patents resulting from applications filed on or after June 8, 1995, subject to the payment of maintenance fees as provided by 35 U.S.C. 41(b) and any extension as provided by 35 U.S.C. 156 or any disclaimer under 35 U.S.C. 253.

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(12) **United States Patent**
Guler et al.

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(45) **Date of Patent: Apr. 15, 2025**

(54) **SINGLE PHOTON SOURCE**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

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(62) Division of application No. 18/074,641, filed on Dec. 5, 2022, now Pat. No. 11,971,576, which is a division of application No. 14/934,097, filed on Nov. 5, 2015, now Pat. No. 11,520,105.

(60) Provisional application No. 62/075,452, filed on Nov. 5, 2014.

(51) **Int. Cl.**
G02B 6/122 (2006.01)
B82Y 20/00 (2011.01)

(52) **U.S. Cl.**
CPC ***G02B 6/1226*** (2013.01); ***B82Y 20/00*** (2013.01); *Y10S 977/701* (2013.01); *Y10S 977/949* (2013.01); *Y10S 977/95* (2013.01)

(58) **Field of Classification Search**
CPC .. B82Y 20/00; Y10S 977/701; Y10S 977/949; Y10S 977/95; G02B 6/1226
See application file for complete search history.

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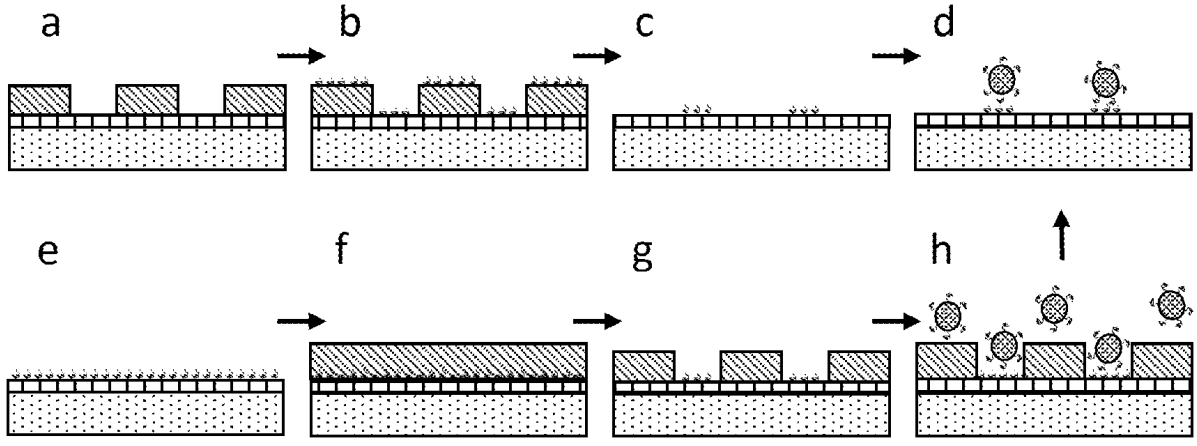
(57) **ABSTRACT**

A method for producing a single photon source includes functionalizing a top surface of a plasmonic thin film to form a functionalized thin film, depositing a polymer on top of the functionalized thin film, lithographically patterning the polymer to form patterned functionalized sites, and targeting nanodiamond particles to the patterned functionalized sites.

12 Claims, 2 Drawing Sheets



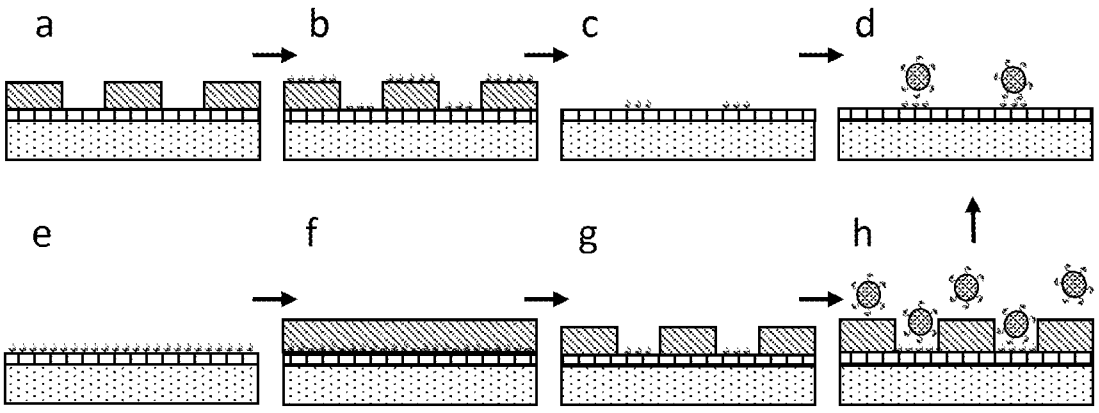


Fig. 1

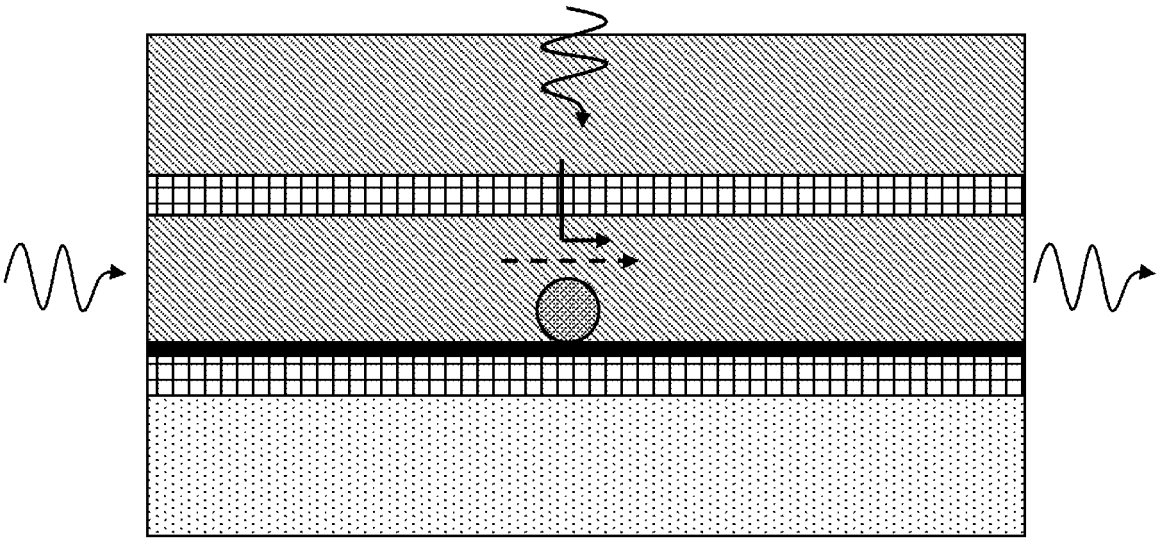


Fig. 2

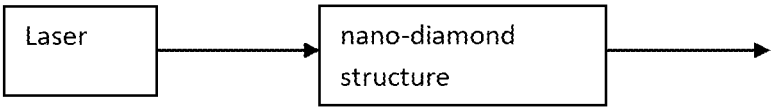


Fig. 3

SINGLE PHOTON SOURCE

REFERENCE TO RELATED APPLICATIONS

The present application is a division of U.S. patent application Ser. No. 18/074,641, entitled "Single Photon Source," filed Dec. 5, 2022, which is a division of U.S. patent application Ser. No. 14/934,097, entitled "Single Photon Source," filed Nov. 5, 2015, now U.S. Pat. No. 11,520,105, issued Dec. 6, 2022, which claims the priority benefit of U.S. Provisional Application No. 62/075,452, entitled "Single Photon Source," filed Nov. 5, 2014, each disclosure of which is incorporated by reference herein.

FIELD OF INVENTION

The invention related to single photon emission systems. Single-photon sources have a broad range of applications in quantum communication, quantum computing and quantum metrology.

BACKGROUND OF THE INVENTION

A single photon source can be defined as a light source that produces photons that are separated in time. This emission of photons separated in time is also known as photon antibunching. Nano-diamonds can be used as an emitter for single photon sources. Color centers in nano-diamonds are prominent candidates to generate and manipulate quantum states of light, as they are a photostable solid-state source of single photons at room temperature and a very stable molecular configuration [See, for example, I Aharonovich, S Castelletto, D A Simpson, C-H Su, A D Greentree & S Prawer. "Diamond-based single-photon emitters", IOP publishing, pp. 1-4]. As color centers are spatially separated in a rigid diamond structure and exhibit sufficient brightness, they can be addressed individually by an excitation laser. Out of more than 500 color centers only 10 have been identified as bright, stable single photon emitters that have demonstrated antibunching characteristics.

Single photon emission systems are used in secure data transmission in quantum communication systems to prevent an unauthorized access to the data. The data is transmitted in a form of pulses of single photons.

SUMMARY

The present invention comprises a metal/insulator/metal waveguide system for the enhancement of single photon emission from nano-diamonds.

In some aspects, the waveguide system is supported with plasmonic nanostructures for improved or new functionalities such as spectrally selective or directional reflection and transmission.

In some aspects, the waveguide system is supported with high refractive index dielectric nanostructure arrays for improved or new functionalities such as spectrally selective or directional reflection and transmission.

In some aspects, the properties of the plasmonic or dielectric nanostructures are modulated via electronic or optical methods for dynamic tuning of functions described above.

In some aspects, the nano-diamond particles are spatially distributed over a lithographically patterned array via chemical or electrostatic bonding.

BRIEF DESCRIPTION OF DRAWINGS

FIG. **1** illustrates ordered assembly of nanoparticles via surface functionalization of lithographically assigned nano-diamond sites. FIG. **1** (*a-c*) shows lithographic patterning of a polymer on top of a plasmonic thin film. FIG. **1** (*e-g*) shows a slightly different scenario where the surface functionalization is done before polymer coating.

FIG. **2** shows light coupling from the top or bottom of the substrate.

FIG. **3** shows schematically the nano-diamond structure excitation by a high power laser.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

A colloidal assembly of a nanodiamond combined with a surface functions as substrate/nanoparticle system. A lithographic patterning is used for controlled staging of the nanodiamond. A surface functionalization is achieved by surfactants with different functional groups at the boundary of substrate and particles. The attachment is of chemical or electrostatic nature.

FIG. **1** illustrates ordered assembly of nanoparticles via surface functionalization of lithographically assigned nano-diamond sites. Among many scenarios, two of the exemplary procedures are given for illustrative purposes. FIG. **1** (*a-c*) shows lithographic patterning of a polymer on top of a plasmonic thin film. Functionalization of the top surfaces of the metallic film and the polymer and subsequent removal of the polymer leaving functionalized sites on the plasmonic surface. The nanodiamond with functionalized surface is then selectively targeted to the patterned sites. FIG. **1** (*e-g*) shows a slightly different scenario where the surface functionalization is done before polymer coating. Then, polymer is coated over the functionalized substrate and patterned with lithographic methods. In this embodiment, the polymer surface remains bare without surfactants. FIG. **1** *h* shows the attachment of the nanodiamond to the functionalized sites on the metallic film. Removal of the polymer leads to the patterned nanodiamond assembly as illustrated in FIG. **1** (*d*). The spatial distribution of nanoparticles can be designed for efficient collective response and the pattern can be realized via lithographic methods including but not limited to photolithography, electron beam lithography, nanoimprint lithography, and soft lithography techniques together with roll-to-roll processing for large scale manufacturing.

Coupling of an electromagnetic wave to the nanodiamond is achieved via several variations of routines. One of the methods described here is the design of a metal/insulator/metal waveguide structure encapsulating the nanoparticle. FIG. **2** illustrates a structure designed that allows easy fabrication steps. A metallic thin film is deposited on a substrate, it is further modified by plasmonic or high index dielectric nanostructures that can be either one of arrayed nanoantennae structures or a set of nanostructures designed as metasurfaces with multiple functionalities such as spectral selectivity, directional reflection or transmission, and field confinement. The metasurface properties can be modulated via electronic or optical methods for dynamic tuning of one or more of the functions mentioned above. The particle is placed on top of the nanostructured thin film via the methods described in FIG. **1**. A dielectric material is deposited on top of the nanoparticle. A simple modification to the method is performed by depositing a thinner layer (which is a half of the total dielectric layer thickness) of dielectric film before the staging of the nanodiamond. The rest of the dielectric layer can be further deposited and encapsulated in the dielectric layer. The thicknesses of the first and second dielectric layers is used for aligning the particle vertically. After the particle is covered by the dielectric layer, another

metallic thin film is deposited in order to achieve a metal/insulator/metal waveguide structure for specific wavelengths and modes. In this design, light coupled into the waveguide structure efficiently couples to the nanoparticle and further improvement or multifunctionalities is added by the use of plasmonic or high index dielectric nanostructures.

The scheme described in FIG. **2** is also designed for light coupling from the top or bottom of the substrate. In this case, metallic thin film on the excitation side is designed thinner in order to achieve high pump incoupling efficiencies while the nanostructured back thin film is designed for directing the emitted photons into one direction of the waveguide. In this method, incoupling is enhanced by using an optical diode surface that allows high transmission in one direction and high reflection in the other. It is also possible to design the incoupling surface a spectrally selective layer that allows high transmittance for pump wavelengths and high reflection for emitted photon wavelengths.

In this design, it is possible to increase the pump coupling efficiency or emitted photon efficiency by means of parameters including but not limited to the metallic or dielectric materials, layer thicknesses, light wavelengths, nanostructure shapes and dimensions etc.

FIG. **3** shows schematically the nano-diamond structure excitation by a high power laser.

The description of a preferred embodiment of the invention has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise forms disclosed. Obviously, many modifications and variations will be apparent to practitioners skilled in this art. It is intended that the scope of the invention be defined by the following claims and their equivalent.

What is claimed is:

1. A method for producing a single photon source, comprising:

(a) functionalizing a top surface of a plasmonic thin film to form a functionalized thin film;

(b) depositing a polymer on top of the functionalized thin film;

(c) lithographically patterning the polymer to form patterned functionalized sites; and

(d) targeting nanodiamond particles to the patterned functionalized sites.

2. The method of claim **1**, further comprising:

addressing individually by an excitation laser each color center in the nanodiamond particles thereby producing a single photon emission.

3. The method of claim **1**, wherein targeting nanodiamond particles to the patterned functionalized sites includes chemically bonding the nanodiamond particles to the patterned functionalized sites.

4. The method of claim **1**, wherein targeting nanodiamond particles to the patterned functionalized sites includes electrostatically bonding the nanodiamond particles to the patterned functionalized sites.

5. The method of claim **1**, further comprising:

depositing a dielectric material layer over the nanodiamond particles.

6. The method of claim **5**, further comprising:

depositing a second plasmonic thin film over the dielectric material layer.

7. The method of claim **1**, wherein lithographically patterning the polymer on top of the functionalized thin film includes at least one of photolithography, electron beam lithography, nanoimprint lithography, or soft lithography.

8. A method for producing a single photon source, comprising:

(a) functionalizing a top surface of a plasmonic thin film;

(b) depositing a polymer over the top surface of the plasmonic thin film;

(c) removing one or more portions of the polymer to form patterned functionalized sites on the top surface of a plasmonic thin film;

(d) depositing nanodiamond particles onto the patterned functionalized sites;

(e) depositing a dielectric material layer over the nanodiamond particles; and

(f) depositing a second plasmonic film over the dielectric material layer.

9. The method of claim **8**, wherein depositing nanodiamond particles onto the patterned functionalized sites includes chemically bonding the nanodiamond particles to the patterned functionalized sites.

10. The method of claim **8**, wherein depositing nanodiamond particles onto the patterned functionalized sites includes electrostatically bonding the nanodiamond particles to the patterned functionalized sites.

11. The method of claim **8**, further comprising:

directing an excitation laser toward a color center of at least one of the nanodiamond particles thereby producing a single photon emission.

12. The method of claim **8**, wherein removing one or more portions of the polymer includes utilizing at least one of photolithography, electron beam lithography, nanoimprint lithography, or soft lithography.

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