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A View at Nanophotonics

Reena Kulkarni[1], Priyadarshini K Desai[2], Keerti Kulkarni[3]

[1, 2, 3]B.N.M Institute of Technology, Department of Electronics and Communication Engineering,
12th Main Road, Banashankari 2nd Stage, Bangalore 560070, India

Abstract: ***Nanotechnology being highly interdisciplinary field is captivating the world by offering amazing features and applications. One of the many application areas of nanotechnology is nano-optics or Nanophotonics, which deals with study of light and its interaction with matter in the nanometer regime. This control over light at the nanoscale has not only unveiled a plethora of new phenomena but has also led to a variety of relevant applications, including new venues for integrated circuitry, optical computing, solar, and medical technologies, setting high expectations for many novel discoveries in the years to come. This paper discusses the various aspects of nanophotonics.***

Keywords: Nanotechnology, Nanophotonics, Fabrication, Solar cells, Optical antennas

1. Introduction

Nanotechnology is the science and engineering at the scale of atoms and molecules to manipulate and use materials and devices in nanometer scale. Photonics is the technology of generating and harnessing light and other forms of radiant energy whose quantum unit is the photon. Nanophotonics is where photonics merges with nanoscience and nanotechnology, and where spatial confinement considerably modifies light propagation and light-matter interaction.

Photonics materials and devices have played a pervasive role in communications, energy conservation, and sensing since the 1960s and 1970s. Nanophotonics have contributed to advances in optical microscopy and nanoscopy. The following sections discuss nanophotonics and its applications.

2. Introduction to Nanophotonics

Interactions and sub wavelength of various substances are calculated with the help of nanophotonics**,** which includes all the phenomena that are used in optical sciences for the development of optical devices. With light analyzed at the nanoscale to exploit optical phenomena, nanophotonics can challenge existing technological limits and help deliver superior photonic device.

The main objectives of nanophotonics research is to control the optical energy and its conversion on the nanometer scale by combining the properties of metal, organic, semiconductor, organo-metallic, polymers and dielectric materials to create new, combined states of light and matter often called meta-materials[1].

Nanophotonics has opportunities ranging from telecommunications to health and energy: photonic circuits that are not only smaller but faster and consume less energy; nano-optical sensors able to detect the chemical composition of molecules at ultralow concentrations; and new solar cell designs for enhanced light absorption.

The scaling down of optics and spectroscopy to the length scale of molecules is not simply a matter of making things smaller; the optical phenomena and spectroscopic behavior at the nanoscale are different from those at the macroscopic scale. Well-known examples are the negative refractive index created by metamaterials [1,2], the quantum confinement observed in the absorption and luminescence spectra of semiconductor nanoparticles and the plasmon resonances of silver and gold nanoparticles.

3. Materials for nanophotonics devices

Today, nanophotonics is devoted to creating new materials with functionality that is not ordinarily available by processing natural elements, alloys, or compounds. The elements of periodic table are cast into a form that is not normally found in nature.

Using metallic and dielectric nanostructures precisely sculpted into two-dimensional (2D) and 3D nanoarchitectures, light can be scattered, refracted, confined, filtered, and processed in fascinating new ways that are impossible to achieve with natural materials and in conventional geometries[3]. Materials used in nanophotonics devices are examined for their scattering efficiencies and Q factors of the magnetic Mie resonance.

The plethora of 2D materials together with their heterostructures, which are free of the traditional "lattice mismatch" issue, brings new opportunities for exploring novel optical phenomena. Many layered materials in their bulk forms have been widely known and utilized for a long time. For example, graphite and molybdenum disulfide (MoS_2) are used as dry lubricants due to their layered nature: atoms are strongly bonded within the same plane but weakly attached to sheets above and below by van der Waals forces [4]. This weak interlayer interaction makes the extraction of single or few-layer of atoms possible, leading to the burgeoning research on 2D materials

Compared to traditional three-dimensional photonic materials such as gallium arsenide (GaAs) and silicon (Si), 2D materials exhibit many promising properties like: their surfaces are naturally passivated without any dangling bonds, making the integration of 2D materials with photonic structures such as waveguides and despite being atomically thin, many 2D materials interact with light strongly.

Unique optical properties of 2D materials enable many important device applications in nanophotonics. Graphene attracts significant attentions for photo-detection due to its strong interaction with photons in a wide energy range and its high carrier mobility, making it a promising candidate for high speed applications in a broad wavelength range.

Crystalline silicon has been identified as the best currently available material for the realization of dielectric antennas operating in the visible range, with germanium outperforming other materials in the IR band.

In the context of nanophotonic applications, nanoparticles with the magnetic and electric resonances located in the visible or near-IR spectral regions are desired

4. Fabrication and characterization methods

The rapid progress of nanotechnology has enabled tremendous development of methods for semiconductor nanoparticle fabrication. The most illustrative example is presented by silicon, since it is the most frequently used high-index material in the visible and IR ranges owing to its relatively low cost and low imaginary part of the refractive index [4].

The development of fabrication technologies of Mie-resonant high-index nanoparticles has recently been initiated that resulted in the emergence of various techniques, summarized in figure 4.1 in terms of five representative parameters: repeatability, productivity, resolution, positioning control (possibility to place a nanostructure at a certain position immediately during fabrication), and method complexity.

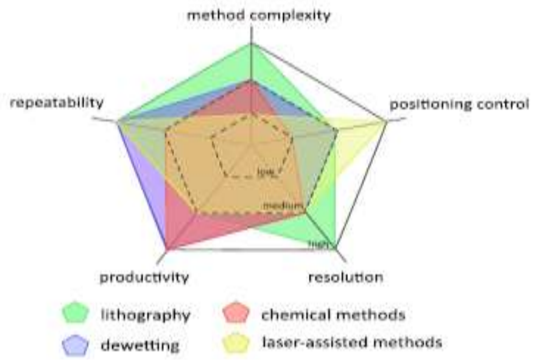

Figure 4.1: Schematic comparison of fabrication techniques of high-index nanostructures.

The techniques to create new nanophotonics devices include both top-down and bottom-up approaches. Making high performance nano-devices requires lithography and patterning, material etching techniques, and material deposition to fabricate.

After designing, fabricating, or chemically synthesizing nanostructures, the sample needs to be characterized with an instrument that resolves to scale less than critical dimensions of nanostructures [5]. Characterization methods include optical techniques, electron microscopy and scanning probe microscopy.

5. Application areas for nanophotonic devices

Improvements in nanofabrication techniques, greater accessibility of high resolution patterning (e.g., electron beam lithography), and pattern transfer processes (e.g., low-damage ion-assisted etching) have produced photonic crystal, micro-disk, and ring resonator devices with exceptional performance [10].

Discovery in nanophotonics has been enabled by the accessibility of optical nanoscale characterization tools such as scanning near-field optical microscopy (SNOM).

Progress in nanophotonics has benefited from advances in structural characterization tools such as atomic force microscopy (AFM), nano-Auger, nano-secondary ion mass spectrometry (nano-SIMS), scanning electron microscopes (SEMs), and transmission electron microscopes (TEM). These instruments have had a major impact on the ability to correlate the size, atomic structure, and spatial arrangements of nanostructure to the observed optical properties.

Some of the other applications include: (i) medical therapies and diagnostics, where the interaction between nanoparticles and light can be used for imaging purposes or to kill cancerous cells through localized heating or even light-induced drug delivery; (ii) data storage, in which plasmonics can help take magnetic storage to new levels of data density through heat-assisted magnetic recording; (iii) nanotagging, in which meta- materials and nanostructured barcodes can be used to combat counterfeiting; (v) new processing techniques for fabrication and lithography at higher resolutions, etc. Two applications of nanophotonics namely, solar cells and optical antennas are discussed in brief in sub-sections 5.1 and 5.2 respectively.

5.1 Solar cells using nanophotonics

Nanophotonics can be applied to existing solar technologies to harness light more effectively to increase efficiency. When sunlight hits a solar panel, a good amount of the potential energy is lost due to it being reflected and scattered. But nanostructures incorporated into a panel can re-direct the scattered light within the solar cell, so that the light travels back and forth within the cell and is trapped inside it.

Using printing techniques, nanostructures with improved light harnessing properties can be printed onto silicon-based solar cells. Alternatively, cells can be designed with nanostructures incorporated into them from the beginning.

5.2 Optical antennas

The light concentration offered by plasmonic nanostructures shows new perspectives to interface light and matter, possibly even down to the level of illuminating a single molecule with a single photon. This level of control becomes possible as light is shrunk in all three dimensions. Optical antennas are nanophotonic elements designed to achieve this functionality, transducing free-space, far-field radiation to localized electromagnetic energy. The simplest nanoantenna is a single metal nanoparticle whose free electrons can support localized plasmon resonances at visible wavelengths, implying that its far-field excitation can result in a strongly localized near-field response. Reciprocally, an optically excited nanoparticle can efficiently radiate light in a controlled way.

6. Challenges

Challenges in nanophotonics include intrinsic losses and CMOS compatibility, and transition from individual devices and components to all-optical circuits and systems . A challenge is to find or produce even higher-density patterned media, with a track pitch similar to the width of plasmonics antenna tip. Challenge for both LED and solar cell applications is the availability of optically thin transparent electrodes required for efficiency and extraction [11]. Some of the other issues include roughness, surface conductivity and transparency. Finally, fabrication of large area high quality graphene sheets also is a challenging task.

7. Conclusion

Nanophotonics as the science and technology of optics is promising new platforms for new nano-devices with growing research opportunities. Nanophotonics has become a major research area and is making advances in optical communications, nano-imaging and sensing applications. Nanophotonics is newly developed very vast and expanding paradigm of nanoscience, and is a unique part of physics/chemistry/materials science because it combines a wealth of scientific challenges with a large variety of near-term applications.

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