Nanophotonics: a multidisciplinary direction

Oleksandr Shpak
Top Master in Nanoscience

Supervisor:
Dr. Maxim Pchenitchnikov

Zernike Institute for Advanced Materials, University of Groningen, Nijenborgh 4, 9747 AG Groningen, the Netherlands

14 August 2009

Abstract

Nanophotonics is a new multidisciplinary frontier. This is a science about optical properties of materials which are built from particles of nanometer scale. This article presents review on main parts of nanophotonic studies. When dealing with optical properties of nanoscale materials one has to use optical near fields. It leads to the fact nanophotonic studies are very much concerned to the scanning near field optical microscopy. First chapter contains an introduction, basic physical concepts of optical near field and overview on scanning near field optical microscopy. There is intense and steadily growing interest in quasi-dimensional nanostructures from the perspective of their synthesis and unique optical properties. Second chapter devoted to fabrication and characterization of nanomaterials for future nanophotonics. The idea of managing of photons instead of electrons in information technologies appears quite long time ago. But realization of this idea becomes possible only with developing of nanotechnologies. Third chapter contains information about research, development, and applications of nanophotonic devices.

Contents

1 Introduction

1.1 Introduction to Nanophotonics

Nanophotonics is a science about optical properties of materials which is built from particles of nanometer scale. Nanophotonics allows to create commercial systems from elements which is much more small and which are working on much more high frequencies that those which have been used before nowadays.

Nanophotonics has two main directions of research. First is connected with investigation of processes which appear in mater after interaction with nanometer scale electromagnetic field (section 1.2). Target not necessarily should have nanometer scale. Lessening of the size of interaction area to the nanometer scale require special techniques. This research is highly tight with near-field scanning optical microscopy (SNOM), which will be discussed in section 1.3.

Second direction is about studying of optical linear and nonlinear properties and chemical reactions of thermodynamically stable nanosized particles induced by the light. In this part of research the size of exciting light can be arbitrary but the object of investigation should have nanometer scale size at least in one dimension.

There two ways to produce nanoparticles. First technique is so-called “from up to down”: milling macroscopic particles into nanometer size particles. The second technique which is genneraly called “from down to up” is connected with assembly of nano-objects by single molecules and atoms. In nature these techniques are broadly used in biological systems when for example complicated protein structures self-assemble from many much more simple molecules. Knowing how to use dipole-dipole interactions, van der Waals forces, hydrogen bonds etc. will allows building of nano-size supramolecular systems for future generations of information technologies. Chapter 2 contains review over some resent publications in fabrication and characterization of nanomaterials for future nanophotonics.

Panel 1. Abbreviations, and Acronyms

SNOM – scanning near-field optical microscopy
SPP – surface plasmon polaritons
FRET – Förster resonance energy transfer
FDTM – finite-difference time domain method
DOS – density of states
QDs – quantum dots
QWs – quantum wells
NQDs – nanocrystal quantum dots
NIR – near infrared
PFCB – perfluorocyclobutane
PL – photoluminescence
CT – charge transfer
STM – scanning tunneling microscopy
FOM – figure of merit

Future demands in the storage density of the optical disc memory is 156Gb/cm^2, which can not be fabricated or read due to the diffraction limit of light because it corresponds to 25 nm size of single bit pit. Novel nanometer-sized materials can be used for future devices. To operate at sub-wavelength scale (to overcome diffraction limit) we need to use optical near field technologies. And 156Gb/cm^2 demand becomes the subject of nanophotonics. There are much more applications of nanophotonic studies then optical data storage. Nano-sized structures for laser cavities, femtosecond pulse generation, nanometer-sized resolution of photochemical vapor deposition and photolithography, nano-waveguides and logical optical schemes for information technologies, they are all concern to nanophotonics. Chapter 3 contains few examples of resent research, development, and applications of nanophotonic devices.

1.2 Optical Near Field

One can not reduce the size of operating devises beyond the diffraction limit to nanometer scale as long as propagating light is used. To overcome diffraction limit one can use optical near field. Optical near field is generated on sub-wavelength size scale by irradiating the propagating light. Primary excitations in a nanometer-scale material are induced in such a manner that spatial phase of excitations is independent of the incident light. Spatial distribution of the optical near field energy depends on the aperture size.

Optical near field is generated by the electronic dipoles induced in sub-wavelength zero-dimensional nanometer-sized particles. Particles are much smaller then the wavelength of the incident light leads to the fact that alignments of induced dipoles are independent of the spatial phase of the incident light. However it depends on the size, structure and conformation of the particle.

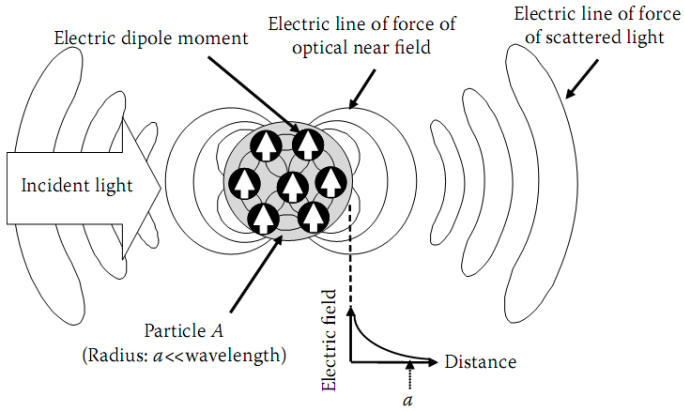

Figure 1 | Optical near field generation. [1].

Science beyond diffraction limit can be realized only by using optical near field (which corresponds to the systems with quasi zero-dimensional topography). Evanescent or guided waves can not be used. The two dimensional evanescent light and one-dimensional guided wave are generated by the periodic alignment of the electric dipoles depending of the spatial phase of the incident light. In evanescent wave these dipoles are induced near the two dimensional material surface and in line-guided wave dipoles are generated along one-dimensional waveguide axis. Because of this dependence some components of wave vectors have real numbers. These real numbers puts waves in to the category of diffraction-limited light waves.

Figure 1 shows classical model of optical near field generation. Electric dipoles are excited by irradiating a nanoparticle A with incident light. Characteristic radius of particle is denoted *a*. The optical near field electric lines of forces starts from the positive charges of the electric dipole and terminate on the negative charges. These fields diverge very quickly and don't propagate to the far field. The scattered light which is shown in a way of closed loops propagates to the far field. Because of the fact that the particle is much smaller then the wavelength of incident light, special phase do not determine the alignment of the electric dipoles. The decay length and spatial distribution of the optical near field can be controlled with fabricating nanostructures with different size, conformation and structures.

The most common theoretical models to calculate optical near-fields are Green's function method and computational electrodynamics modeling technique, finite-difference time domain method (FDTM). In FDMT the time-dependent Maxwell's equations in partial differential form are discretized using central-difference approximations to the space and time partial derivatives [22]. Then the electric field vector components in a volume of space are solved at a given instant in time; then the magnetic field vector components in the same spatial volume are solved at the next instant in time. The process is repeated until the desired transient or steady-state electromagnetic field behavior is fully evolved.

Linear and nonlinear nanophotonics of surface plasmon polaritons (SPP) attracts great deal of interest. The SPP wavelength in a given frequency range may be much shorter than the wavelength of free space photons. Such tight spatial localization of the SPP field gives rise to considerable field enhancement and gives many interesting nonlinear optical phenomena, which occur at very low light levels. From the theoretical point of view it's very interesting that the nonlinear nanophotonics of SPPs may be helped by the quantum gravity analogy [21]. This analogy may be very useful since compared to quantum gravity, SPP nanophotonics is a relatively young field when various effects of quantum gravity are being studied for considerably longer time. As the number of SPP quanta involved in these effects is reduced, quantum effects play more and more important role in nonlinear optical processes on namometer size sale. Experimentalists move close to realization of quantum nonlinear nanophotonic devices (see section 3.1).

Other theory was developed by M. Ohtsu and K. Kobayashi [1] which consider optical near field simultaneously like the interaction and energy transfer between nanosized particles. This perspective is essential because the interaction
and energy transfer are indispensable for nanophotonic devices and nanophotonic fabrications. They tried to avoid the complexity of describing all of the behaviors of nanometric and macroscopic subsystems rigorously, because we are interested only in the behavior of the nanometer scale subsystem. The macroscopic subsystem is expressed as a mixed state of material

excitation and electromagnetic fields. The projection operator method is effective for describing the quantum mechanical states of these systems. Under this treatment, the nanometer scale subsystem is regarded as being isolated from the macroscopic subsystem, whereas the functional form and magnitude of effective interactions between the elements of the nanometer scale subsystem are inluenced by the macroscopic subsystem. Two nanoparticles can be considered simultaneously as being isolated from the surrounding macroscopic system and as interacting by exchanging exciton–polariton energies.

Theoretical models do not always describe processes properly. Conventional optics theories do not provide any physically intuitive pictures of nonpropagating nanometric optical near fields because these theories were developed to describe the light waves propagating through macroscopic space or materials. Reaching of good understanding of nonlinear quantum nanophotonics is a very important current goal. Now the main way to learn optical properties on nanometer scale is experimental observations. Next section describes near-field optical microscopy, the field which is very much concerned with nanophotonics.

1.3 Near-Field Optical Microscopy

Because of diffraction (Relay criterion) investigation on interaction of nano-sized objects with classical optical methods not allows obtaining of desirable information. One must use electromagnetic field which is localized in nanometer scale. This is so called near-field region where the radius of interaction is much smaller than the wavelength of the emitted light. Only in this case one can get proper spatial resolution. There are two main approaches for studying on interaction nano-objects with light:

- Limitation of sizes of source of the light
- Restriction of region in which radiation interacts with a sample

Firstly was the idea of restriction of source light sizes. This method was practically implement at the beginning of 1970-s. Images with resolution less then the wavelength where obtained. As a source of radiation was quarts crystal with aluminum cover with micro size openings. Sample should be located at the distance of few nanometers from the source. Later on using of sharp glass wires where proposed. Effectiveness of such glass probes leads to fast spread of commercial scanning near-field optical microscopes. At the present time optical fibers with sharpened endings with metal cover are using. This technology allows separation of far-field from near-field. The former is not able to spread through small openings.

Similarly to the atomic force microscopy in SNOM position of probe is regulating with a feedback system which are measuring interaction force between the tip and the surface. One can get not only optical but also topographic image.

Resolution of SNOM is restricted because of size of the tip and also because of diameter

of openings. The production of such fibers (tips) is very difficult engineering challenge and each fiber is unique. The size of opening (aperture) was possible to achieve less then 30 nanometers [2]. Maximum spatial resolution is equal to several tens of nanometers.

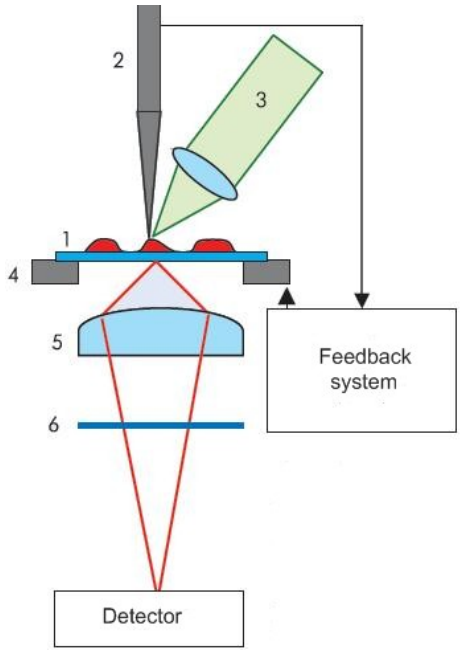

Figure 2 | The typical scheme of the experiment on apertureless near-field optical microscopy: 1-sample, 2-probe, 3- irradiation, 4-XYZ scanner, 5-collecting lens, 6-polarizer.

Spatial resolution can be approved with apertureless scanning near-field optical microscopy [23]. Figure 2 shows a scheme of apertureless near-field optical microscopy. This technology uses very sharp needle (tip). Radiation is scattered by the edge and allows the resolution which is restricted only by the radius of curvature of the tip. During scattering one have both near-field and far-field but if the tip is close enough to the sample then near-field prevail to give the signal.

Another method of limitation of source light sizes is restriction of interaction area between probe and excited electromagnetic field from the sample. To reduce the region of probe-sample interaction the mechanism of resonance energy transfer (Förster transfer) was proposed [4]. Förster resonance energy transfer (FRET) is a mechanism of energy transfer between two chromophores (chromophore is a part of a molecule responsible for its color) through nonradiative dipole–dipole coupling. In the near field region (typically less than 10 nm) an excited chromophore emits a virtual photon which is instantly absorbed by a receiving chromophore. These virtual photons are undetectable, because their existence violates the conservation of energy and momentum. Quantum electrodynamics gives exact calculations for this phenomenon. Donors (fluorescent centers) initially in its electronic excited states, may transfer energy to an acceptors on the sample. Very low concentration of fluorescent centers on the probe has been used that only one center was located on the tip [3]. In this case special resolution was determined not by the diameter of the opening but by the Förster radius which is in order of 0.5-5 nanometers. The Förster radius denotes the distance between two fluorescent dyes, in which 1/2 of radiation-free energy via FRET can be observed. The FRET efficiency can be calculated as follows: $R_0^6/(R_0^6+r^6)$. Here R_0 is the Förster radius, and r is the distance between the two fluorescent dyes.

Restriction of region in which radiation interacts with a sample can also be achieved by using of phenomenon of local

electromagnetic field increasing near sharp spike (Figure 3). This method of local enhancing of signal intensity (Tip Enhanced Raman Scattering) was realized by Anderson and co-workers [5]. Carbon nanotubes where used as a sample because they are highly structured. It was shown that lateral resolution equal to 11 nm can be achieved.

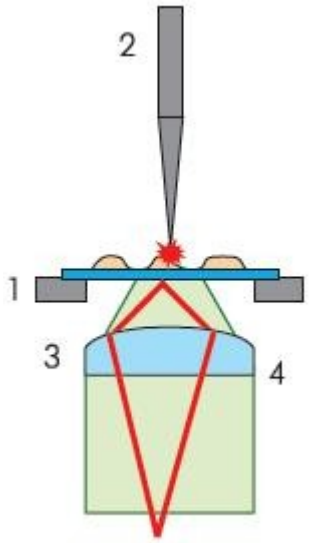

Figure 3 | The typical experimental scheme for the localization of the field due to a giant enhance an electromagnetic field near a metal very sharp tip: 1 - sample, 2 -probe, 3 - XYZ scanner, 4 - lens

Close to rough metal surfaces electromagnetic field can significantly be increase. This effect is widely used in spectroscopy of Surface Enhanced Raman Scattering. In some cases, the signal fluorescence near the metal surfaces can also be increased. Local fluorescence enhancement is described in [24]. For the separation of enhanced signal from the background using of the oscillating needle was suggested. In this case, the enhancement of the signal is not constant. Signal enhance only when the tip is close enough to the surface. Changes in the intensity of fluorescence on the distance between the tip and the surface is given in Fig.4

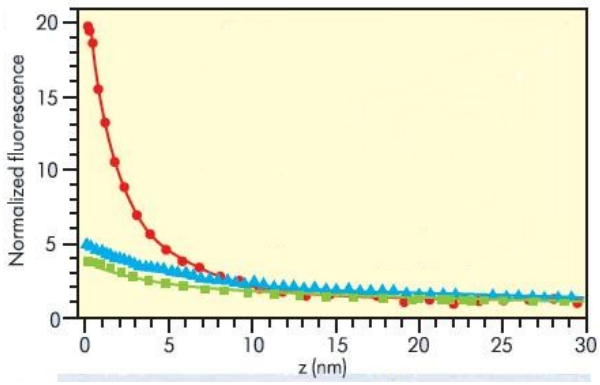

Figure 4 | Changes in the intensity of fluorescence on the distance between the tip and the surface [24].

Scanning near-field optical microscopy based on local enhancement of electro-magnetic field requires more research on registration and analysis of enhanced signal. But information which is got in this method is unique and new and it allows investigation of optical properties for future nanophotonic materials with resolution higher then other methods. SNOM has very high interest among scientists and is extremely developing. Future development of considered methods certainly will allow getting valuable information about structure and operation of nanophotonic objects and materials.

2 Fabrication of Nanophotonic Materials

2.1 InAs/GaAs Self-Assembled Quantum Dots for Nanophotonics

Fabrication of nanomaterials atom-by-atom is very slow and impractical for producing commercial nanoscale devices. Nanoscale operating materials usually contains millions of atoms and they have to be assembled simultaneously but not consecutively. Concurrent organization of million of atoms is possible with self-assembly.

With present technologies it is possible to create nano-structures that confine fundamental charge carriers in semiconductors in so small region that they properties are described by quantum mechanics. Low dimensional structures quantum wells, nanowires, and quantum dots (2D, 1D, and 0D structures respectively) can be formed from different materials. Distribution function of density of states (DOS) on energy is altered in such structures. With changing of DOS distribution electromagnetic properties of material can also be changed. Particularly quantum dots (QDs) have been studied for zero-dimensional quantum confinement in semiconductors as light emitters and efficient gain materials in the visible and near infrared. Also quantum dots have been used for laser resonant optical cavities with low threshold and low line width.

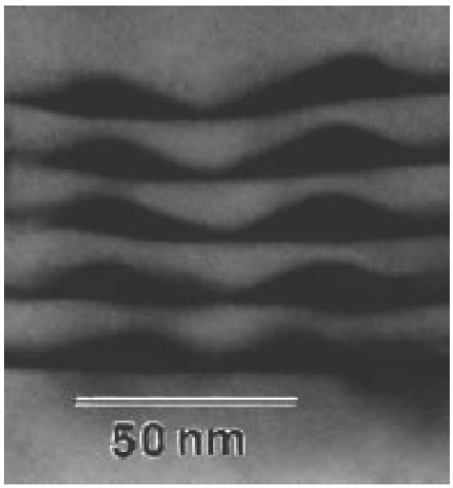

Figure 5 | Electron micrograph cross section through the InAs/GaAs quantum dots sample. Quantum dots that are 30 nm in diameter and <10 nm high and is designed so that the fundamental optical resonance occurs near 1,300 nm (one of the telecommunication wavelength bands) at room temperature. [6].

QDs have discrete DOS which extremely high influence carrier dynamics. But energy spacing between the discrete levels become compatible to characteristic room temperature thermal energies only for quantum dot sizes around 10 nm. InAs/GaAs quantum dots have been produced by using Stranski-Krastanow self-assembled technique. Alternating layers where grown by using molecular beam epitaxy (Figure 5). In this technique layers exhibits a large lattice mismatch, and when the critical thickness is reached, compromise between bulk strain and surface tension starts spontaneous buckling of surface and nucleation of three dimensional islands i.e. formation of quantum dots. These structures are produced with the highest level of dimensional control but they exhibits low

luminescence efficiency because of defects between the quantum dot and the host semiconductor. The surface density, size, and shape of self-assembled QDs can be controlled with changing substrate temperature, quantum dot composition, and growth rate.

Properties of the quantum dots can be characterized by illuminating the material with a short-wavelength laser and then by measuring of the re-emitted light spectrum. Figure 6 shows three quantum dot optical resonance peaks. Each peak corresponds to transitions between confined electron and hole states. Shape which governs the carrier wave functions of self-assambled quantum dots is not under proper control and can not be reliably measured. For this continues wave and time-resolved spectroscopic techniques can be used. Time resolved spectroscopic technique can distinguish between carrier-carrier and carrier-phonon interactions. At room temperature three distinct temporal decay rates corresponds to three differential transmission signals. The electron-hole radiative recombination corresponds to the longest time constant ~900 ps. Then at time rate ~100 ps experiments observe electron activation. Holes can be more efficiently thermally activated because their confinement levels have much smaller energy spacing with thermalization rate ~1 ps. Thus dynamics of carriers into self-assembled quantum dots can be fully characterized using time-resolved photoluminescence.

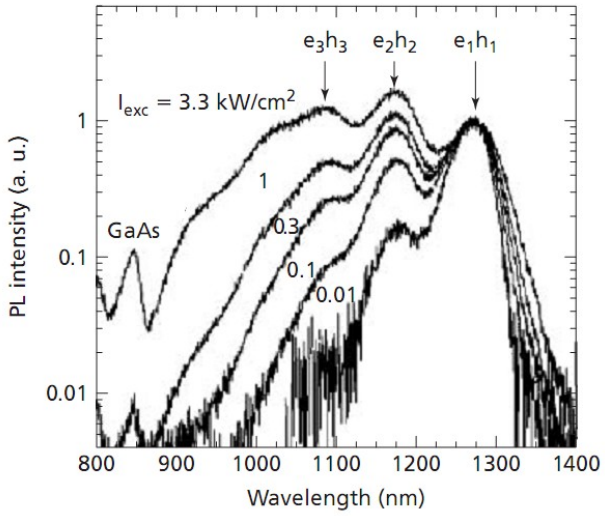

Figure 6 | Photoluminescence spectra of the quantum dots for different laser excitation intensities [5].

2.2 Nanocrystal Quantum Dots

Another promising technology for range of nanophotonic applications is nanocrystal quantum dots (NQDs). They are chemically synthesized semiconductor particles with discrete electronic-level structure. By changing of their constituent material and controlling their size, absorption and emission wavelength can be varied from visible to near-infrared (NIR) spectral range. NQDs usually consist of a crystalline semiconductor few nanometers size core and a surrounding shell of a higher band-gap semiconductor material. The shell provides the confining voltage for the core electrons, protects it from the surroundings, reduces undesirable effects at the surface of the NQD, prevents from clumping and makes NQDs soluble in some polymers.

NQDs can be distributed in polymer-based organic robust matrix and then integrated

into optical devices. Organic polymers are very convenient and potentially low-cost building-block materials for many optical circuits because they are transparent in a wide spectral range, easy processed, and have low curing temperature which one needs do not effect NQDs properties. Liquid mixture of NQDs integrated into polymer can be easily processed. It can be cured, etched, molded, and spin-coated into the desirable shape on various substrates.

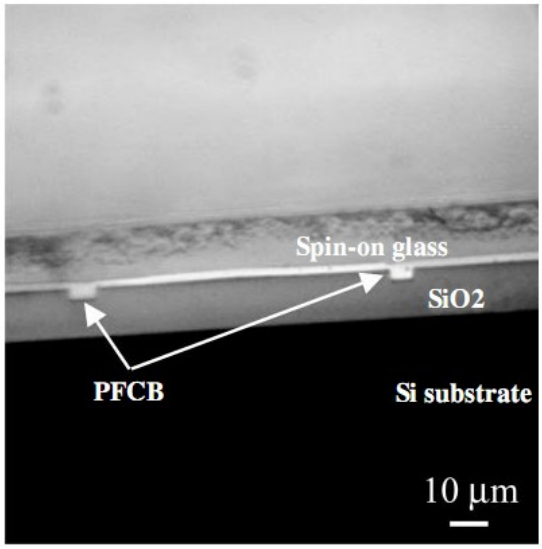

Figure 7 | Optical image of a polished facet of a PFCB/NQD polymer ridge waveguide structure. The ridge is 3 microns high [5].

Dinu and her group have demonstrated a working integrated perfluorocyclobutane (PFCB) polymer/NQD devise on silicon substrate [5]. Polymer has very low optical loss on 700-1500 nm wavelength range, good thermal stability, low dielectric constant, and low polymerization temperature. PbSe and InAs core NQDs have been used. They where 1550 nm wavelength optically active and about 8 nm in diameter (Fig. 7). The capping material originally deposited in the NQD synthesis was chosen to be compatible with the polymer matrix.

A thick layer of silica glass was thermally grown on top of a silicon wafer. It was used as the lower protective coating for the waveguides. By reactive etching method 3 micron deep and 2 micron in width trenches where then etched on the glass cladding. Then the film was slowly baked 12 hours at T=120 °C in a nitrogen atmosphere to prevent oxidation and changing optical properties of NQDs. It is important that NQDs/PFCB refractive index has to be higher than the top and bottom glass protecting wafers to provide light guiding. This trench-filling method is better then photolithography, because polymer experiences less processing steps and consequently NQDs are less likely to be effected by the fabrication. Besides, this technique allows good control of the width and the thickness of the wavequides.

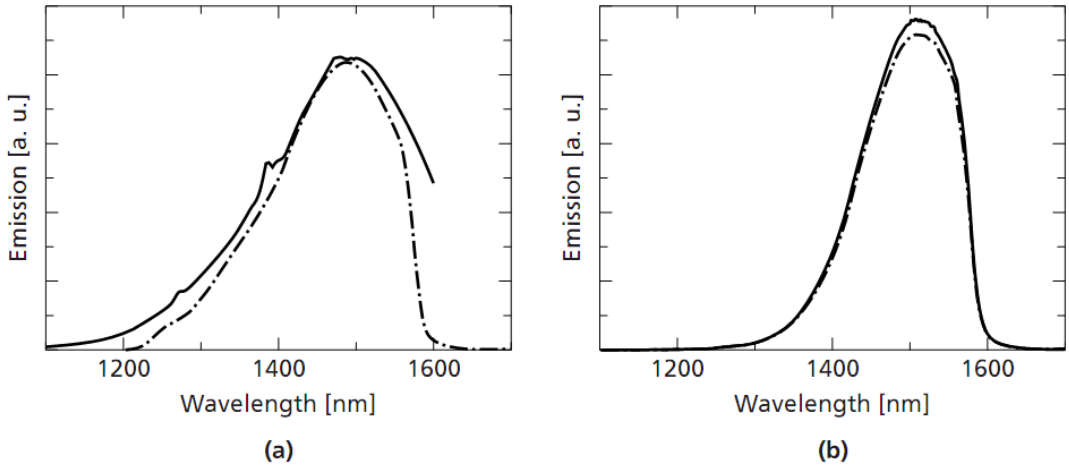

Figure 8 | Optical emission from nanocrystal quantum dots. Emission spectra taken for PbSe NQDs (a) and InAs NQDs (b) before (solid lines) and after (dash-dotted lines) the fabrication process. [7].

Figures 8 show the test of the preservation of NQDs optical properties. This test demonstrates that the optical properties of the NQDs were almost not affected by the various stages of the process. To prove necessity of being processing in nitrogen atmosphere to prevent oxidation, PFCB was polymerized in ambient atmosphere where optical properties were changed (NQDs wavelength was blue-shifted).

Trench-filling method of producing nanocrystal quantum dots allows incorporating and controlling of optical properties in photonic integrated systems. It can have a lot of applications in laser devices, optical switches, optical logic gates, amplifiers etc. The possibilities are very enticing. Future research and developing will make technology commercially available. Of course, much more work must have to be done to improve this new technique to be proper for using in real world applications.

2.3 Molecular-Scale Imprinting

Self-assembly requires good mobility, but device-utilization requires stability. Self-assembly occurs in the physisorption phase when atoms or molecules attached to surface by physical forces.

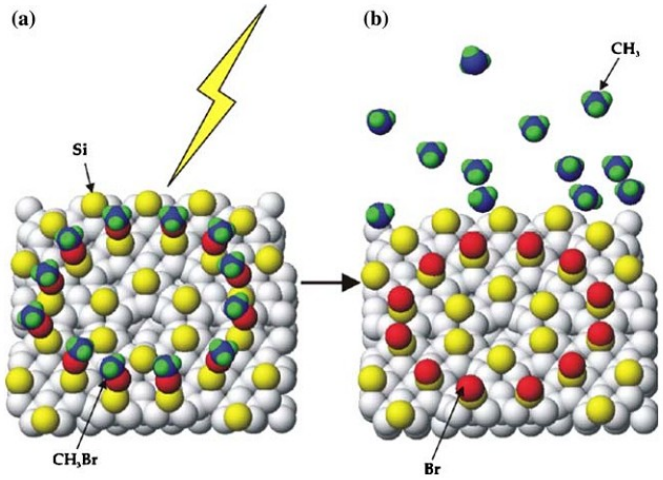

Figure 9 | Schematic of (a) physisorbed CH_3Br on Si(111) with Br pointing down, and (b) chemisorbed Br on middle adatom positions after photolysis or electron impact at temperature 50 K [7].

Device-utilization implies condensing of charge or charge transfer (CT) through self-assembled structure. Each additional electron or hole on physisorbed nanoparticle will alter the interaction between nanostructure and underlying substrate, and will tend to loose configuration. That's why the second fabrication stage is needed to immobilize physisorbed nanostructures. This second process is called molecular-scale imprinting. During this stage physisorbed addends become chemisorbed by induced chemical reaction. The process is schematically shown in figure 9. Chemical reaction consists of the transfer of total or part of the physisorbed molecule, previously loosely attached to the surface, and form much more strong bounds are forming.

It is important to highlight that self-assembly diffusion takes finite time. To induce chemical reaction one need to deliver energy through direct short pulses implantation of heat, incident electrons (scanning tunneling microscopy) or light (photolysis). By controlling imprinting characteristic time constants one can maintain proper diffusion and consequently proper self-organization.

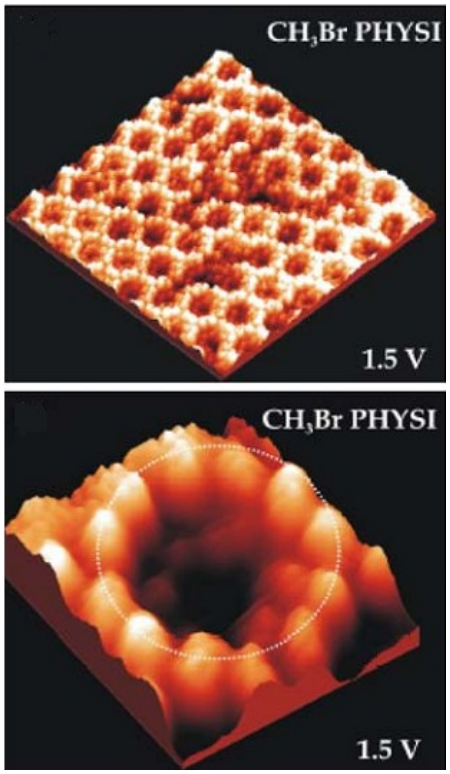

Figure 10 | Upper picture: STM image of physisorbed CH_3Br on the 50K Si(111) substrate. Lower picture: zoomed-in indicated by dotted line STM image of a single 12-molecule ring of physisorbed CH_3Br on Si(111) surface. [7].

Also one needs to have fully localized reaction at the atomic level. Only retained enough molecular-scale pattern can exhibit chemisorptions without lateral displacement across the surface. There are two a priori criteria for highly localized reaction: maintaining minimum translational energy along the reaction coordinate and direction of approach of the reagent should be normal to the surface plane [7]. These two conditions for highly localized reaction mean that the atom or molecule approaching the surface should have a minimum momentum across the surface to prevent reaction at a distance from the original point of impact.

But in practice neither of these two criteria is necessary in a broad category of reagents. It appears that the approach to the surface not needs to be strictly perpendicular. And the reaction not needs to be induced at its threshold energy.

Study about atomic and molecular motions in chemical reactions is a reaction dynamics.

One example of molecular scale imprinting is physisorbed self-assembled pattern of methyl bromide (CH_3Br) adsorbed at a Si(111) surface at 50 K surface temperature. CH_3Br forms circles with 12 well ordered molecules forming one circle. Figure 10 shows scanning tunneling microscopy (STM) image of silicon substrate with CH_3Br physisorbed on a wafer.

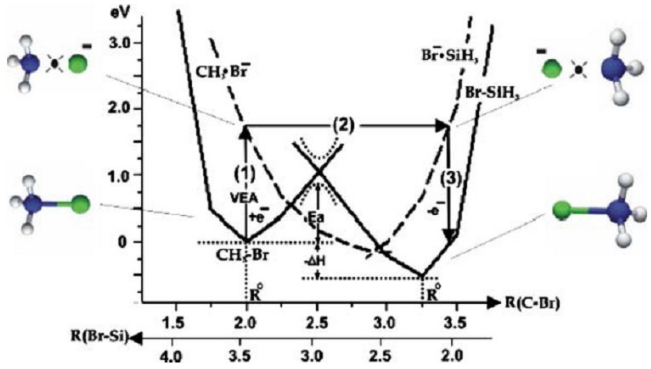

Figure 11 | Model of the charge-transfer (CT) reaction with co-linear C–Br–Si. The dots indicate repulsion. VEA = vertical electron affinity; E_a = activation energy; – ΔH = heat of reaction [7].

Figure 12 shows the chemisorbed Br to silicon substrate after 193 nm irradiation on the unchanged surface voltage of V_s=1.5 V and on the changed surface voltage V_s=2.5 V. With increasing voltage from 1.5 to 2.5 V one can light-up Br-Si sites. Proof that chemisorptions had occurred is that the circular pattern had survived when heated to 200°C through irradiation. Figure (11) shows that Br-atoms are highly localized on Si-atoms directly on the places of original rings of physisorbed CH_3Br.

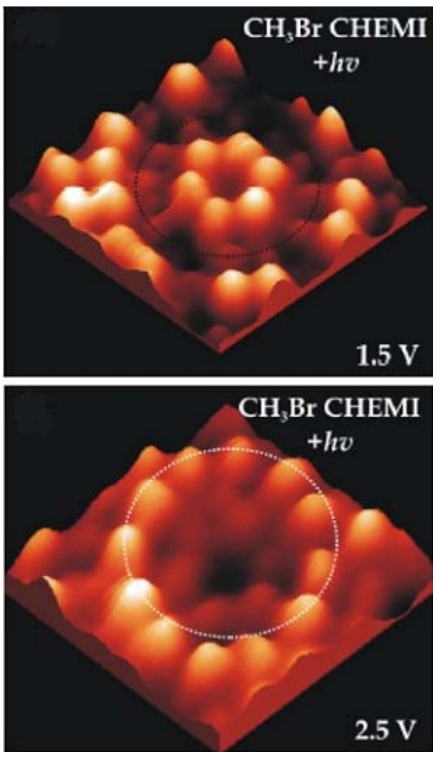

Figure 12 | Upper picture: STM image of chemisorbed Br on Si(111) surface after photolysis of physisorbed CH_3Br(ad) at 50 K. Br beneath dotted circle appears as depressions on the middle adatoms with surface voltage V_s = 1.5 V. Lower picture: STM image of chemisorbed Br imprints on the middle adatoms indicated by a dotted circle as in upper picture but with surface voltage V_s = 2.5 V. [7].

Three consequent stages for this molecular imprinting process are: charge-transfer to the methyl bromide from the silicon surface, $CH_3Br + e^- \rightarrow CH_3Br^-$, transfer of Br^- from methyl bromide to the surface $CH_3Br^- + SiH_3 \rightarrow CH3 + Br^- \cdot SiH_3$, and charge-transfer in $\sim 10^{-13}$seconds back to the silicon surface, $Br^- \cdot SiH_3 \rightarrow Br^- - SiH_3 + e^-$. Model of the charge-transfer reaction with co-linear C–Br–Si. Is shown on Figure 11.

3 Nanophotonic Devices

3.1 Near-Field Optical Memory

Very promising application of nanophotonics is high density optical information storage with an illumination mode SNOM. Data storage can be performed by using technique of spatially localized photochemical reaction induced by the near-field femtosecond laser pulses.

Figure 13a shows an example of near-field optical memory device. Series of domains are written and read with one-photon excitation. Each domain (with diameter of 120 nm) is a data bit. Surrounding fluorescence area is clearly distinguishable from black domains (black is due to loss of fluorescence). Photobleaching is linear. Figure 13b shows an image of a grating pattern with fringe periodicity of 290 nm. Which is 34 500 lines per cm. This technique can be improved with nonlinear photo bleaching.

Figure 14a shows an analogous optical image of series of domains but both written and read with two-photon excitations. In this case a bit size is smaller and is about of 70 nm, which shows that higher density storage can be achieved with near-field-photon excitations. Much higher density storage are possible, because of quadratic dependence on excitation intensity limits the effective excitations to a smaller volume for a two-photon excitations. Figure 14b shows a grating patter with two-photon excitations. Grating periodicity is 62 500 lines/cm.

Blu-ray technology use blue-violet laser with a wavelength of 405 nm to read and write information. Conventional CD and DVD use red and infrared lasers with a wavelength of 650 nm and 780 nm, respectively. This Blu-ray technology decreasing in wavelength together with the use of larger numerical aperture (0.85, compared with 0.6 for DVD) has allowed narrowing of the track twice in comparison with conventional DVD-ROM (up to 320 nanometers) and increasing the density of data recording. But still near-field optical memory gives higher memory density storage.

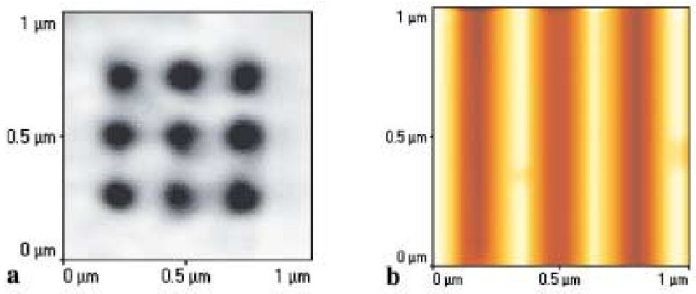

Figure 13 | data bits and (b) grating pattern written and read back with one-photon excitation [8]

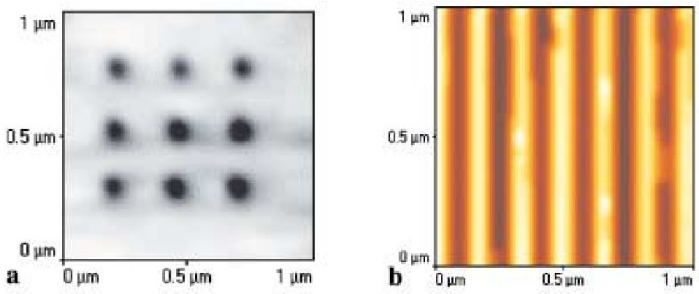

Figure 14 | data bits and (b) grating pattern written and read back with two-photon excitation [8].

3.2 Nanophotonics in Lasers

Large quantum confinement in 3 dimensions enhances density of states at band edge and leads to low lasing threshold. Controllable emission wavelength of QDs allows making laser at any colors, which are not available for semiconductor laser at present time. Difference of energy in electron states in QDs is large enough to provide proper population inversion, which results in decreasing of lasing threshold.

Another quite interesting materials from QDs and QWs for laser cavities are semiconductor nanowires. Many unique optical properties of nanowires can be obtained by controlling of discrete energy states and a sharp distribution of DOS as their size diminishes. Epitaxially and vertically grows of nanowires on silicon substrates are possible. Arrays of Si nanowires were synthesized by an aqueous electroless etching method [9]. The nanowires varied from 20 to 300 nm in diameter with an average diameter of approximately 100 nm.

Lieber and co-workers have produced electronically driven n-type CdS single-nanowire laser [10]. At low currents broad peaks emerge but for a current above 200 µA the emission shows very sharp peaks. Nanowire laser cavity structures possess high Q and relatively small mode volume, suitable for efficient next generation laser systems. 1-D nano-structures are very

promising for next generation nanophotonic technologies.

3.3 Nano-waveguides

The idea to replace the manipulation of electrons to the manipulation of photons is a very old one. Almost forty years ago we heard predictions of a replacement of the classical computers to the optical.
However, enormously huge amounts of data are already path through the optical cables, but, ultimately, still we are dealing with electronic computers.

It would seem that the laser technologies, optical fibers, LEDs, and photodetectors, lenses and prisms allow building of photonic analogues of silicon chips. It turns out, that to learn how to manage short pulses of light into nanometer size patterns is not so simple.

Important steps in this direction have done recently, the American experts at Berkeley National Laboratory and the University of California. They have learned how to create the finest optical conductors and how to integrate them into extraordinary miniature circuits. The leader of this research is Peidong Yang. They where able to collect the lasers and waveguides into semiconductor nanostructures that illustrate how light can be transmitted between nodes. They have also introduced a new application area for optical nanometer sized waveguides in liquid media, which is very useful for research in biology and chemistry. These nanometer sized waveguide, created by Yang and his colleagues are solid crystals, with one millimeter length, but only a few tens or hundreds of nanometers thickness.

These tapes and fibers can serve as optical waveguides to guide the photons through a complex scheme also including photoluminescence. Complete photon logic system on a single chip with a conventional electronic circuits size have not been established yet. But researchers are approaching this point. They showed how nano-scale lasers created with the use of zinc oxide and gallium nitride are connected with tin oxide nanometer-scale optical fibers such as light and forced to run short pulses from node to node, rotate, and branch. The main characteristic of logic systems is the figure of merit (FOM) of an optical switch It's even more important than the switching speed. FOM as is defined as $F = C/(t_{sw}P_{sw}V)$, where C, V, t_{sw}, and P_{sw} are the ON–OFF ratio, volume of the switch, switching time, and switching energy, respectively [15].

In addition, the network on the basis of tin oxide can act as optical filters to provide the control of wavelength of pulses and separate them by various "exits". This is useful when designing logic circuits for photonics. And perhaps the most intriguing result of this work include the creation and testing of optical nanowaveguides that can transport the light, depending on its interaction with the liquid. The properties of the fluid can change the parameters of the signal at the output of the waveguide.

This opens the possibility of constructing optical chips which can analyze the chemical or biological composition of droplets placed on the surface. Specialists believe that the

full photon Internet might provide information transfer on the speed of 160 gigabits per second.

The time which will be held before the optical machine will conquer the world is very hard to predict. For mass production of components for nanophotonic devices one have to learn how to create nano-waveguides in huge commercial quantities with tremendous accuracy of their geometry.

About proposals for the transfer of information light pulses, instead of electrical. Indeed, the two intersecting electric wires must be isolated from each other, otherwise the electrical currents mix which lead to loss of signal. Another problem is that wires have electrical resistance, and they heat by passing an electric current through them. This leads to the consumption of energy and limits the amount of information which can be transmitted.

Two or more beams of light can pass through each other without mixing and loss of information. Even beams of light going in one direction, do not mix. A loss of energy in the transmission of light pulses is much smaller than in the transmission of electrical signals. These advantages of light led to rapid development optical communication links. Fiber optic cables tied up entire countries. Computers based on nanophotonic technology can work one hundred times faster with much higher density of data storage.

4 *Conclusions*

In this article, fundamentals for nanophotonic systems are presented along with fabrication of nanophotonic materials and its applications

Developments of theoretical studies which describe the main physical concept of nanophotonics (optical near-field interactions) drop far behind the development of experimental research.

SNOM was reviewed. It allows getting site specific imaging of nanophotonic materials with high resolution and high contrast.

Also we discussed a number of potential nanophotonic device opportunities. Trench-filling method of producing nanocrystal quantum dots, molecular scale imprinting on the example of physisorbed self-assembled pattern of methyl bromide (CH_3Br) adsorbed at a Si(111), and InAs/GaAs Self-Assembled Quantum Dots where reviewed. We showed how unique opportunities can arise when one controls parameters of fabrication of self-assembled nanostructures.

Nanophotonisc has not been applied commercially yet because of the technological difficulties of creating such devices and integrating them into macroscopic objects. Only with the development of nanotechnology it became possible to use light pulses in nanometer scale.

Nanophotonics offers numbers of opportunities for both fundamental research and applications.

5 Acknowledgments

I would like to thank my supervisor Dr. Maxim Pchenitchnikov from Zernike Institute for Advanced Materials who kindly proposed me this topic and helped with writing my paper.

6 Bibliography

1 M. Ohtsu, K. Kobayashi, T. Kawazoe, T. Yatsui, Makoto Naruse et al., "Principles of nanophotonics," Taylor & Francis Group press (2008).

2 V. Sandoghar, J. Mlynek, "Prospectives of apertureless SNOM with active probes". – J. Opt. A: Pure Appl. Opt. 1, 523–530(1999).

3 J. Michaelis, C. Hettich, J. Mlynek, V. Sandoghdar. "Optical microscopy using a single-molecule light source", Nature 405, 325–328 (2000).

4 S. A. Vickery, R. C. Dunn "Combining AFM and FRET for high resolution fluorescence microscopy". – Journal of Microscopy 202, 408–412 (2000).

5 N. Anderson, A. Hartschuh, L. Novotny. "Near-field Raman microscopy", Materials Today, 50–54, (2005).

6 M. Dinu, R. Rapaport, G. Chen, H. R. Stuart, R. Giles, "Nanophotonics—Quantum Dots, Photonic Crystals, and Optical Silicon Circuits: An Excursion into the Optical Behavior of Very Small Things" Bell Labs Technical Journal 10(3), 215–234 (2005)

7 Harry E. Ruda, John C. Polanyi, Jody (S. Y.) Yang et al., "Developing 1D nanostructure arrays for future nanophotonics" Nanoscale Res Lett (2006) 1:99–119

8 Y. Shenp., N. Prasad "Nanophotonics: a new multidisciplinary frontier", Appl. Phys. B 74, 641–645 (2002)

9 I. Hochbaum, R. Chen, R.D. Delgado, W. Liang, E.C. Garnett, M. Najarian, A. Majumdar, and P. Yang, Nature, 451, 163 (2008)

10 X. Duan, Y. Huang, R. Agarwal, C. Lieber, Nature 421, 241 (2003)

11 I.V. Bondarev, Journal of electronic materials, Vol. 36, No. 12, (2007)

12 J. Bloch, J. Shah, L. N. Pfeiffer, K. W. West, and S. N. G. Chu, "Optical Properties of Multiple Layers of Self-Organized InAs Quantum Dots Emitting at 1.3 mm," Appl. Phys. Lett., 77 (2000), 2545–2547.

13 Z. Jaksic and M. Maksimovic et al., "Fabrication-induced disorder in structures for nanophotonics," Microelectronic Engineering 83 (2006) 1792–1797

14 Peter I. Borel, Brian Bilenberg, Lars H. Frandsen et al., "Imprinted silicon-based nanophotonics" Optics express 1263 / Vol. 15, No. 3 / (2007)

15 Tadashi Kawazoe, Takashi Yatsui, Motoichi Ohtsu, "Nanophotonics using optical near fields" Journal of Non-Crystalline Solids 352 (2006) 2492–2495

16 Yu Huang, Xiangfeng Duan, and Charles M. Lieber "Nanowires for Integrated Multicolor Nanophotonics" Small Journal 2005, 1, No. 1

17 "New concepts for nanophotonics and nanoelectronics", C. R. Physique 9 (2008) 1–3

18 W.E. Moerner, R.M. Dickson, D.J. Norris, "Single-molecule nanophotonics in solids" Materials Science and Engineering B48 (1997) 169- 174

19 J. R. Guest, Xiaoqin Li, T. H. Stievater, D. G. Steel, and D. Gammon, "Direct Probing of Quantum Dots through

Linear and Nonlinear Nano-Optics" phys. stat. sol. (b) 234, No. 1, 435–442 (2002)

20 J Yongseok, V M Kozenkov, S A Magnitskiy, N M Nagorskiy, "Optical orientation of azo dye molecules in a thin solid film upon nonlinear excitation by femtosecond laser pulses", Quantum electron, 2006, 36 (11), 1056–1057.

21 I. Smoluaninov, "Nonlinerar Nano-Optics Of Surface Plasmons at the "Plank Scale"", Modern Physics Letters B, Vol. 20, No. 7 (2006) 321–342

22 A. Taflove and M. E. Brodwin "Numerical solution of steady-state electromagnetic scattering problems using the time-dependent Maxwell's equations". Microwave Theory and Techniques, 1975, IEEE Transactions on 23: 623–630.

23 Inouye Y., Kavata S. Near-field scanning optical microscope with a metallic probe tip. – Opt.Lett. 19, 159–161 (1994).

24 Gerton J.M., Wade L.A., Lessard G.A., Ma Z., Quake S.R. Tip-Enhanced Fluorescence Microscopy ar 10 Nanometer Resolution, Physical Review Letters 93, 180801 (2004). 20. Anderson N., Hartschuh A., Novotny L. Near-field Raman microscopy, Materials Today, 50–54, (2005).