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Finland–Japan Workshop on Nanophotonics and Related Technologies

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Welcome from the organizer

Nanophotonics is a novel technology that utilizes the optical near-field, which is the electromagnetic field that mediates the interaction between nanometric particles located in close proximity to each other. Novel devices, fabrication techniques, systems, and sensing have been developed in this regard. By using the intrinsic nature of the optical near-field energy transfer and subsequent dissipation, novel functions and phenomena have been realized that were impossible using propagating light. They constitute examples of *qualitative innovation* in optical science and technology.

It is my pleasure to organize the Finland-Japan Workshop on Nanophotonics and Related Technologies. The speakers invited to this workshop will provide overviews of the current status of their areas of expertise. In addition, recent research highlights will be presented in the form of oral presentations. In particular, this workshop, as suggested by its title, versatile approaches and related topics will widely be covered.

This workshop will provide opportunities for information exchange and sharing, so that the participants can bring their ideas, results, and problems forward for open discussion; such discussion will also provide opportunities to promote new advances and suggest ways of exploring the scientific and technological potential of this new area.

I would like to welcome you all to this workshop and I hope that you will enjoy the stimulating presentations and lively discussions that will ensue during the meeting. I also hope that you will have the opportunity to enjoy the summer here in Espoo. I thank Research Professor Pentti Karioja of VTT for his great help as a co-organizer. I also thank Dr. Makoto Naruse and many others for their active assistance and arrangement. Special thanks are due to VTT Technical Research Centre of Finland and Finnish Funding Agency for Technology and Innovation (Tekes).

Welcome to the Finland-Japan Workshop.

Motoichi Ohtsu

Preface

Nanophotonics is the combination of Photonics and Nanotechnologies, study of the behaviour of light on the nanometer scale and interaction of light with particles or substances at deeply sub-wavelength scale. The benefit of nanophotonics is new functionalities for systems. Functionalities obtained with nanophotonics can be utilized in several fields: optical communications, information processing, data storage, displays, user interfaces, lighting and sensors. In order to estimate the performance and characteristics of the system, the modeling is the first step. In order to be able to utilize the novel functionalities in real systems, the structures need to be fabricated and the performance of the devise needs to be verified experimentally. In the fabrication phase, the tailoring of conventional fabrication processes and development of totally new processing technologies needs to be assessed. The nanophotonics research and development needs multidisciplinary approach. The proceedings of the Finland–Japan Symposium covers an overview on latest research activities on the field of nanophotonics and related technologies in Finland and Japan.

Pentti Karioja

Contents

Rigorous Analysis of Light Polarization in a Light Guide with Sub-wavelength Gratings

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Abstract

Liquid Crystal on Silicon (LCOS) microdisplay is typically less than ½ inch in diameter and are used in Near to Eye Displays or in Picoprojectors. These displays are reflective and the control of light in each pixel is based on change of the polarization of light in the liquid crystal material. The reflective nature of the display requires using Polarization Beam Splitters (PBS) in illumination which enlarges the back focal length of optics and reduces the compactness of the system. In this paper the use of polarization maintaining lightguide instead of the PBS is studied. The back focal length is shortened and the system is more compact. The problem is to design the lightguide so that the contrast of the system is kept in acceptable level. In the ray tracing study the rigorous coordinate transformation method is used in polarization and efficiency calculations.

Introduction

The optical setup of a LCOS based projector is shown in Fig. 1. A cube PBS have been traditionally used as reflective polarizers but wiregrid polarizers are lighter and having air instead of glass in the back focal area makes the optics design easier.

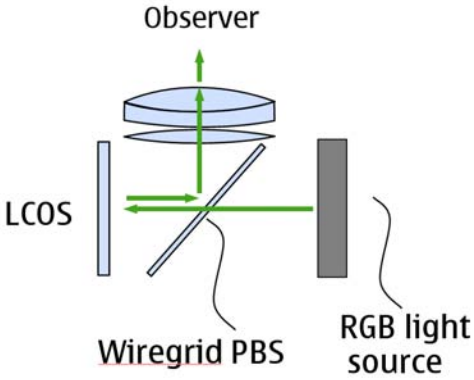

Figure 1. A typical setup of an optical engine with PBS.

The illumination of displays using diffractive lightguides is an established technology [1] but can one construct a polarization maintaining lightguide as shown in Fig. 2. The required function of the light guide is that the lightguide produces highly polarized light (p) towards LCOS and is practically transparent for the other polarization (s). The lightguide should not produce any residual s-polarization towards the lens. The sub-wavelength structures on a lightguide can be very polarization sensitive but maintaining the polarization state inside the lightguide is very challenging as even each total internal reflection (TIR) changes the state of polarization.

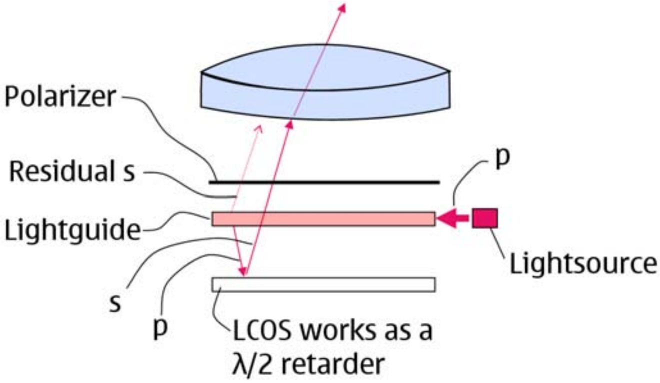

Figure 2. An optical engine using light guide based LCOS illumination.

In the coordinate transformation method (Chandezon-method or C-method) the electric and magnetic fields are given by superposition of two fields $\psi^{E_\pm}$ and $\psi^{H_\pm}$ where the electric field components E_3 (~TM) or H_3 (~TE) are zero. The efficiency of diffraction of the mode *q* is given by a formula [2]

(1)

$$\eta_q^\pm = \left|\frac{S_q^\pm}{S_0^{in}}\right| = \left|\frac{\mathrm{Re}\left\{\left|s_q^{E_\pm}\right|^2 \sum_n \left[\psi_n^{E_\pm}\left(\kappa_3^\pm \Lambda_{np}^{q\pm}\psi_p^{E_\pm}\right)^*\right] - \left|s_q^{H_\pm}\right|^2 \sum_n \kappa_2^\pm \Lambda_{np}^{q\pm}\psi_p^{H_\pm}\left(\psi_n^{H_\pm}\right)^*\right\}}{\mathrm{Re}\left\{\left|s_0^{E_{in}}\right|^2 \sum_n \psi_{n,0}^{E_{in}}\left(\kappa_3^+ \Lambda_{n0}^{0in}\psi_{p,0}^{E_{in}}\right)^* - \left|s_0^{H_{in}}\right|^2 \sum_n \kappa_2^+ \Lambda_{n0}^{0in}\psi_{n,0}^{H_{in}}\left(\psi_{p,0}^{H_{in}}\right)^*\right\}}\right|$$

where the coefficients $\left|s_q^{E_\pm}\right|$ and $\left|s_q^{H_\pm}\right|$ carry the information of the polarization of diffracted fields. These coefficients can be calculated from a matrix formula

(2)

$$\begin{pmatrix} s_p^{E_\pm} \\ s_r^{H_\pm} \end{pmatrix} = M_1 s_0^{E_{in}} + M_2 s_0^{H_{in}} \text{ ,}$$

where the matrices M_1 and M_2 are constructed from the fields $\psi^{E_\pm}$ and $\psi^{H_\pm}$ [2]. Thus it is enough to calculate only once the diffraction problem and get the grating specific fields, and then apply the formulas to any incoming state of polarization (coefficients $\left|s_0^{E_{in}}\right|$ and $\left|s_0^{H_{in}}\right|$). This method makes the rigorous ray tracing possible, because the speed of calculation is not a question any more. Finally the ellipticity and the orientation of the ellipsoid can be easily calculated from the *s*-coefficients.

Results

The analysis shows that the contrast depends much on the angular spread of the light coming out from the lightguide, i.e. depends on the f-number of the optics. In Fig. 3. is shown the calculated contrast of the system having overhanging saw-tooth shape grooves. With the f-number of 3 an average contrast of 100 can be achieved. The contrast depends of course also on other things like the material birefringence which is ignored here.

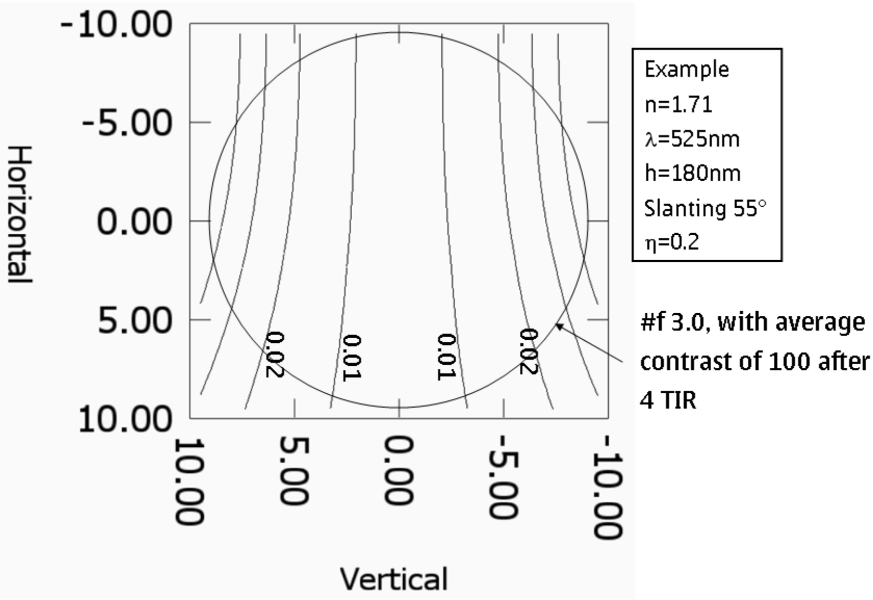

Figure 3. The contours of contrast of a light guide with a saw tooth grating structure.

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Nanophotonics: Exchanging the Dressed Photons

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Quantitative innovation in optical technology is required for future optical information transmission systems, to increase the integration of photonic devices by reducing their size and heat generation. Furthermore, novel applications, such as optical information-processing systems, are expected to result from *qualitative* innovation, by relying on novel functions and operations of photonic devices that are impossible using conventional photonics. Nanophotonics is an innovative type of optical technology that is based on the local interaction between nanometric particles via optical near fields; it was first described by the author [1]. Nanophotonics enables new photonic devices, processes, and systems to meet the requirements of future optical technology, especially with respect to achieving qualitative innovation. Optical near fields are the elementary surface excitations on nanometric particles, i.e., dressed photons that are exchanged between the nanometric particles. Local energy transfer and its subsequent dissipation are possible using optical near fields [2, 3].

Nanophotonics has produced some interesting new devices such as nanophotonic AND- and NOT-gates, and an optical nanofountain. AND-gate operation has been demonstrated by CuCl quantum dots (QDs) [4] and by ZnO nanorod with double quantum wells [5]. For room-temperature operation of NOT-gate devices, we have used InAlAs, a promising candidate material. We fabricated two layers of $In_{0.5}Al_{0.5}As$ QDs using molecular beam epitaxy [6]. They were grown just above the QDs in the lower layer, so that the lower and upper

QDs were aligned vertically owing to the residual lattice strain induced as a result of growing the lower QD. The temporal evolution of the output signal was evaluated. The outstanding advantages of these nanophotonic devices are their low power consumption and small size. We estimated that the power consumption was about five orders of magnitude lower than that of a conventional electronic gate [7]. The optical nanofountain can be used as a far-field to near-field optical signal conversion device to connect a conventional diffraction-limited photonic device to a nanophotonic device [8].

Nonadiabatic processes triggered by optical-near-field interactions have been used as representative examples of nanophotonic fabrication. These processes represent *qualitative* innovation in photochemical vapor deposition and photolithography, suggesting that large, expensive ultraviolet light sources are no longer required, although they are indispensable for conventional adiabatic photochemical vapor deposition, photolithography, and photochemical etching. It also suggests that nonadiabatic photochemical vapor deposition can even dissociate optically inactive molecules (i.e., inactive to the propagating light), which is advantageous for environment protection because most optically inactive molecules are chemically stable and harmless. For example, optically inactive $Zn(acac)_2$ molecules have been dissociated to deposit nanometric Zn particles [9]. In addition, in the case of nonadiabatic photolithography, an optically inactive resist film for electron-beam lithography has been used to fabricate fine patterns [10]. Furthermore, in nonadiabatic photochemical etching has realized an ultra-flat glass surface with the roughness as low as 1.3 Angstrom without using any photomasks [11].

In conventional optical science and technology, light and matter have been discussed separately, and the flow of optical energy in a photonic system has been unidirectional from a light source to a photodetector. By contrast, in nanophotonics, light and matter have to be regarded as being coupled to each other, and the energy flow between nanometric particles is bidirectional. This means that nanophotonics should be regarded as a *technology fusing optical fields and matter*. The term nanophotonics is occasionally used for photonic crystals, plasmonics, metamaterials, silicon photonics, and quantum dot lasers using conventional propagating lights even though they are not based on optical near-field interactions. For the development of nanophotonics, far-reaching physical insights into the local electromagnetic interaction in the nanometric subsystem composed of electrons and photons is required.

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Motoichi Ohtsu received the Dr. E. degrees in electronics engineering from the Tokyo Institute of Technology, Tokyo in 1978. He was appointed a Research Associate, an Associate professor, a Professor at the Tokyo Institute of Technology. From 1986 to 1987, while on leave from the Tokyo Institute of Technology, he joined the Crawford Hill Laboratory, AT&T Bell Laboratories, Holmdel, NJ.

In 2004, he moved to the University of Tokyo as a professor. He has been the leader of the “Photon Control” project (1993–1998: the Kanagawa Academy of Science and Technology, Kanagawa, Japan), the “Localized Photon” project (1998–2003: ERATO,JST, Japan), “Terabyte Optical Storage Technology” project (2002–2006: NEDO, Japan), “Near field optical lithography system” project (2004–2006: Ministry of Education, Japan), and “Nanophotonics” team (2003–

2009: SORST, JST, Japan). He is concurrently the leader of the “Innovative Nanophotonics Components Development” project (2006-present: NEDO, Japan) and “Nanophotonics Total Expansion: Industry-University Cooperation and Human Resource Development” project (2006-present: NEDO, Japan). He has written over 417 papers and received 87 patents. He is the author, co-author, and editor of 55 books, including 22 in English In 2000, he was appointed as the President of the IEEE LEOS Japan Chapter. From 2000, he is an executive director of the Japan Society of Applied Physics. His main field of interests are the nanophotonics and dressed photon technology. Dr. Ohtsu is a Fellow of the Optical Society of America, and a Fellow of the Japan Society of Applied Physics. He is also a Tandem Member of the Science Council of Japan. He has been awarded 14 prizes from academic institutions, including the Issac Koga Gold Medal of URSI in 1984, the Japan IBM Science Award in 1988, two awards from the Japan Society of Applied Physics in 1982 and 1990, the Inoue Science Foundation Award in 1999, the Japan Royal Medal with a Purple Ribbon from the Japanese Government in 2004, H. Inoue Award from JST in 2005, and the Distinguished Achievement Award from the Institute of Electronics, Information and Communication Engineering of Japan in 2007.

Essences of an Optical Near Field and Its Applications to Nanophotonic Devices and Fabrications

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Nanophotonics is a technology using local electromagnetic interactions between small nanometric matters. This interaction, *i.e.*, an optical near-field interaction, causes unique physical phenomena, *e.g.*, an energy transfer to optically forbidden state, a nonadiabatic photochemical reaction, and a photoemission via nonadiabatic transitions, in the nanometric system. In this presentation, I introduce mechanisms of these unique phenomena and their experimental results.

First, I explain the energy transfer between quantum dots via an optical near-field interaction. The energy transfer rate drastically increases by the optical near-field interaction and the transfer time becomes longer than the exciton life time in a quantum dot. If the exciton is utilized as a signal carrier, the operations of nanometric optical device (nanophotonic device), *e.g.*, AND-gate, NOT-gate, optical nanofountain, and the higher functional device, realizes [1–5]. They are single photon devices and their sizes are less than 100 nm [6]. It should be noted that some of the conventional concepts of wave-optics dose not become essential for them, and the nanophotonic devices bring qualitative innovation to the optical device technology.

Second, I introduce the nanofabrication using the nonadiabatic photochemical reaction. The molecules were dissociated even though the photon energy of the optical near field was lower than the electronic transition energy and the dissociation energy of the molecule due to the nonadiabatic photochemical reaction [7, 8]. This unique photochemical reaction is applicable also to other photochemical fabrication methods, such as photolithography [9, 10] and photochemical etching [11]. I introduce highly efficient X-ray grating and polarizer with nanometric structures as the fabricated results.

The nonadiabatic photochemical reaction is based on the optical transition to the vibrational state in a material. The excited material shows the nonadiabatic photochemical reaction. If the material is chemically stable, the excited material relaxes by a photoemission. In this case, the photon energy of the emission becomes higher than that of the excitation light. Finally, I explain the visible photoemission from DCM dye molecular particles by the infrared excitation [12]. This visible photoemission never comes from two-photon process. Therefore, the emission efficiency becomes higher than other up conversion method, when the power of converted infrared light is weak.

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Tadashi Kawazoe was born in Kochi, Japan, on April 5, 1967. He received the B.E., M.E., and Ph.D. degrees in physics from University of Tsukuba, Tsukuba, Japan, in 1990, 1993, and 1996, respectively. He has studied optical nonlinearities in semiconductor quantum dots at the Institute of Physics, University of Tsukuba. In 1996, he joined the faculty of Engineering, Yamagata University, Japan, as a research associate, engaged in research on nonlinear optical materials and devices. In 2000, he has been with Japan Science and Technology Corporation, Japan. Since 2000, He has studied optical devices and fabrication based on an optical near-field interaction. In 2007, he joined the University of Tokyo as a projected associated professor. His current research interests are in the nanophotonic device.

Dr. Kawazoe is a member of the Japan Society of Applied Physics and the Physical Society of Japan.

Nanophotonic Fabrication and Operation

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For future optical transmission systems with high data transmission rates and capacity, we have proposed nanometer-scale photonic devices (i.e., nanophotonics devices) [1]. These devices consist of nanometer-scale dots, and an optical near-field is used as the signal carrier.

To realize nanophotonic device, we use ZnO nanorod quantum-well-structures because ZnO has large exciton binding energy than thermal energy. Through time-resolved near-field spectroscopy of ZnO/ZnMgO nanorod double-quantum-well structures (DQWs), we observed AND-gate operation by controlling the exciton excitation in the dipole-inactive state via an optical near-field [2]. We also observed the dynamic properties of exciton energy transfer and dissipation between chemically synthesized ZnO quantum dot (QD), via an optical near-field interaction, using time-resolved photoluminescence spectroscopy [3]. Furthermore, we successfully increased the energy transfer ratio between the resonant energy states, instead of the radiative decay from the QD.

Since the nanophotonics devices is composed of sub-100-nm scale dots and wires, and their size and position must be controlled on a nanometer-scale to fabricate the device. To realize this level of controllability, this talk reviews bottom-up method using optical near-field. First, we demonstrate that optical near-field desorption can dramatically regulate the growth of metallic nanoparticles during optical chemical vapor deposition. The trade-off between the deposition and desorption due to the optical near-field light allowed the fabrication of a single 15-nm Zn dot [4], while regulating its size and position. For realization of mass-production of nanometer-scale structures, the possibilities of applying such a near-field desorption to other deposition technique such as sputtering, which does not use any fiber probes or photomasks, will be discussed [5]. Finally, we performed a new polishing method that uses near-field etching based on a non-adiabatic process [6], which does not use any polishing pad, with which we obtained ultra-flat silica surface with angstrom-scale average roughness [7].

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From 1999 to 2000, he was a Research Fellow of the Japan Society for the Promotion of Science. From 2000 to 2003, he was a Researcher at the Japan Science and Technology Corporation, Tokyo. Since 2003, he has been a Researcher at the Japan Science and Technology Agency, Tokyo. In 2008, he joined the University of Tokyo as an Associate Professor. His current research interests include nanofabrication using optical near-field and its application to nanophotonics.

Dr. Yatsui is a Member of the Japan Society of Applied Physics. Dr. Yatsui received 1st prize in Paper Contest from IEEE Student Branch at Tokyo Institute of Technology in 1998, and the excellent research presentation award form the Japan Society of Applied Physics in 2000, and Tejima Doctoral Dissertation Award from Tejima Foundation in 2001.

Hierarchical Optical System Based on Nanophotonics

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“Nanophotonics” uses the local interaction between nanometric particles *via* optical near-fields to bring “qualitative innovation” to the field of optical technology [1]. Optical near-field interactions respond hierarchically at the nanometer scale, allowing unique nanophotonic functions [2]. We defined two kinds of hierarchical optical near-field interactions: those between optical far- and near-fields (*Hierarchy 1* in Fig. 1(a)), and those within the optical near-field (*Hierarchy 2* in Fig. 1(a)). The former hierarchical property is based on the fact that optical near-field interactions can be explicitly distinguished by light. The other hierarchical property exists at the scale of optical near-field interactions. It occurs due to the varying physical behavior of the system at different scales. The appearances of certain nanostructures depend on how we observe them as shown in Fig. 1(b). In this presentation, we will demonstrate these hierarchical effects numerically and experimentally by using several prototype optical elements.

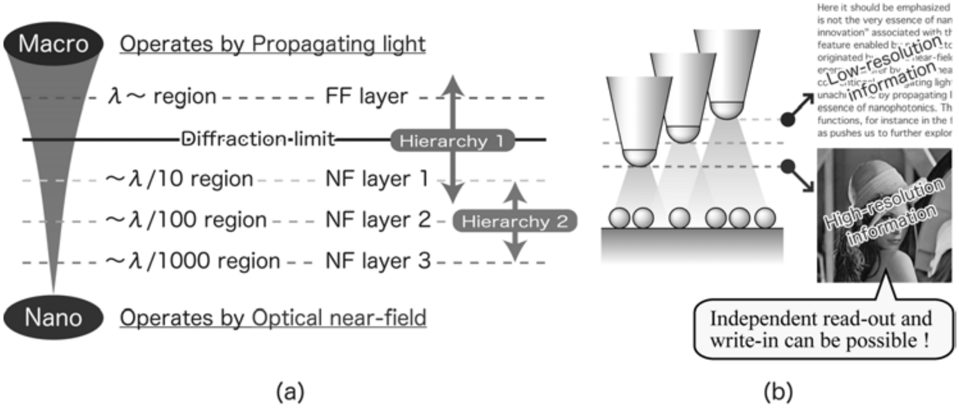

Figure 1. (a) Basic concept of the hierarchy in optical near-fields. (b) Schematic diagram showing the scale dependency of the optical near-field based on the observation distance, and the application to hierarchical memory retrieval.

For engineering hierarchical system, the size, shape, and composition of nanostructures are important physical entities. For example, nanostructures provide different hierarchical responses if they contain different internal structures or compositions even when they are equal in shape and size. We experimentally demonstrate such material-dependent optical near-field hierarchy using core–shell-type nanostructures composed of gold and silver [3]. Such material-dependent systems would be significantly resistant to counterfeiting since a copy of the nanomaterials' shape is not enough to retrieve system information. This suggests that hierarchical properties in optical near-fields may have practical applications to memory and security-related applications.

On the other hand, our "nanophotonic hierarchical hologram" is defined as a hologram that has multiple observing layers both in optical near- and far-field [4]. It can be created by adding a nanometric structural change (< 100 nm) to a conventional hologram (> 100 nm). In principle, the phenomenon occurring at a subwavelength scale does not affect the function induced by propagating light. Therefore, the visual aspect of the hologram is not affected by such a small structural change on the surface. We exploit the physical difference between the propagating light and optical near-field, where the former is associated with conventional holographic patterns obtained in optical far-fields, whereas the latter is associated with nanometric structure accessible only *via* optical near-fields.

These works were supported by the research project of the New Energy and Industrial Technology Organization (NEDO), Japan, the Special Coordination Funds for Promoting Science and Technology, Japan, and the University of Tokyo Global COE Program: Secure Life Electronics.

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Naoya Tate was born in Osaka, Japan, on March 24, 1978. He received the B.E. and M.E. in physics, and Ph.D. degrees in information science from Osaka University in 2000, 2002, and 2006, respectively. From 2006 to 2007, he was a Researcher of the Core Research for Evolutional Science and Technology (CREST) at the Japan Science and Technology Agency (JST), Tokyo. In 2007, he joined the University of Tokyo as a Project Assistant Professor of “Nanophotonics Total Expansion: Industry-University Cooperation and Human Resource Development” project at the New Energy and Industrial Technology Development Organization (NEDO). His main field of interest is implementation of several applicative processing systems based on information photonics. Dr. Tate is a member of the Optical Society of America (OSA) and the Japan Society of Applied Physics.

Post-scaling CMOS Devices Heterogeneous Integration on Si Platform

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The performance of Si LSIs has been enhanced over 30 years by increasing the number of transistors with the Moore's law. As is well known, the scaling rule of the Si transistor has made it possible to enhance the performance of the LSIs. However, the miniaturization of the transistors becomes increasingly difficult due to the physical limitations, and the conventional scaling rule will not be enough to enhance the performance of the LSIs. Therefore, some breakthrough technologies are strongly required for the Si LSI in order to enhance the device performance even in the post-scaling era. Heterogeneous integration of III-V compound semiconductors and Ge on the conventional Si CMOS platform is one of the promising candidates to overcome the scaling limit of the conventional Si LSI because of their high carrier mobilities. In addition, the III-V and Ge enable us to integrate photonic devices on the LSI.

In this presentation, we review the recent activities for the post-scaling semiconductor devices. III-V/Ge MOSFETs and monolithic integration of Ge photodetectors and Ge MOSFETs have been successfully demonstrated by the heterogeneous integration of III-V/Ge with the direct wafer bonding [1] and the Ge oxidation condensation [2].

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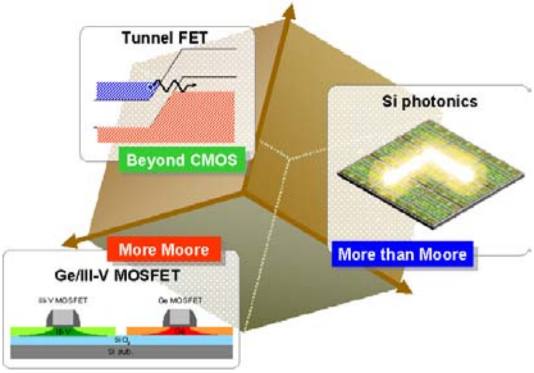
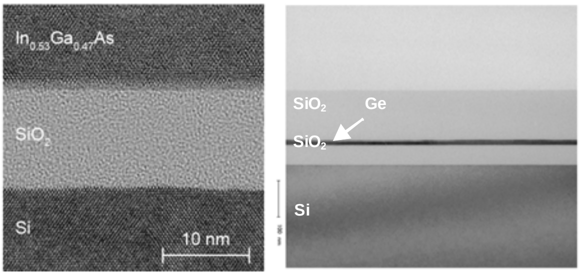


Figure 1. Post-scaling CMOS devices by heterogeneous integration.



(a) III-V-OI on Si (b) Ge-OI on Si

Figure 2. Heterogeneous integration on Si substrate.

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Dr. Takenaka is a member of IEEE/LEOS, the institute of Electronics, Information, and Communication Engineers (IEICE), and the Japan Society of Applied Physics (JSAP). He received the Young Scientist Award for the Presentation of an Excellent Paper in 2003 form the JSAP, and the Young Researchers' Award in 2005 from the IEICE.

Optical Activity in Planar Nanostructures

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The discovery of the surface-plasmon-enhanced optical activity in two-dimensional array of chiral metal nanoparticles [1–3], in which polarization effect is enhanced by a strong coupling of photons with surface plasmons [4, 5], has attracted interest to planar chiral metamaterials in photonics for light polarization control. However, in metal nanostructures, optical losses impose severe restrictions on photonic applications. We recently demonstrated that this difficulty can be overcome using an on-waveguide chiral photonic crystal that surpasses metal-based chiral metamaterials in terms of the rotation power and transparency [4]. We showed that in the planar chiral nanostructure, the coupling of the normally incident light wave with low-loss waveguide mode results in a dramatic enhancement of the optical activity. One may anticipate that the giant polarization rotation in all-dielectric chiral structure that we discovered will open new opportunities in polarization control for light emitters, polarization selective photo-sensors and polarization switching devices.

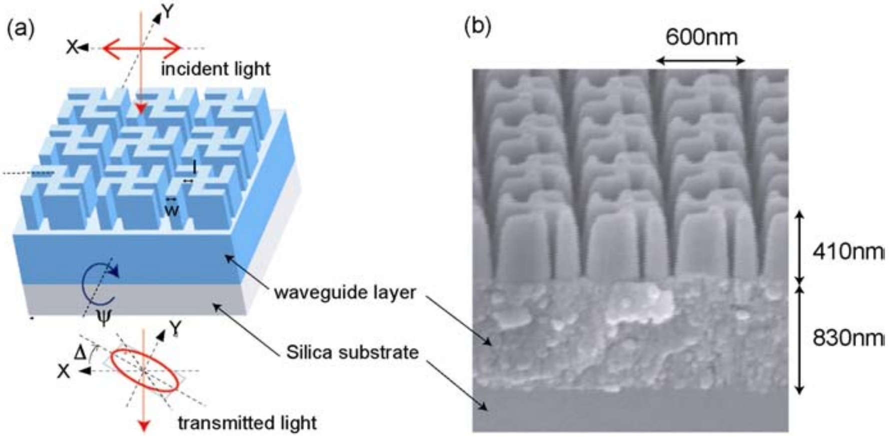

Figure 1. (a) Structure of the sample. ψ is the rotation direction for p-polarized light. Δ represents the polarizatio aximuth rotation angle. The widths of the gammadion line and opening are w = 120 nm, 1 = 70 nm, and the period is 600 nm. (b) SEM image of the right-handed sample. The thicknesses of the chiral layer and waveguide layer are shown.

The planar chiral structure consists of 410 nm thick TiO2 chiral nanograting with a period of d = 600 × 600 nm, TiO2 waveguide layer and silica substrate. The structure was designed to possess a four-fold rotational symmetry about the substrate normal. Measurements were performed in a wavelength range from 520 nm to 1550 nm.

The spectra of the chirality-induced (i.e. independent on the polarization azimuth of the incident light wave) polarization azimuth rotation θ and ellipticity θ of the transmitted wave at normal incidence are shown in Fig. 2. Both θ and θ have opposite signs for structures with left and right senses of twist in the whole spectral range while transmission is twist independent. The achieved polarization azimuth rotation is as high as 25.6 degrees at a wavelength of 630 nm, i.e they are about 10 times bigger than that obtained in mertal nanostructures. Comparison of Figs. 2a–c allows us to conclude that the spectral positions of the resonance features in the transmission spectra (Fig. 2a) coincide with those in the polarization spectra (Figs. 2b and c). This indicates that the chirality-induced polarization effect is associated with waveguide resonances.

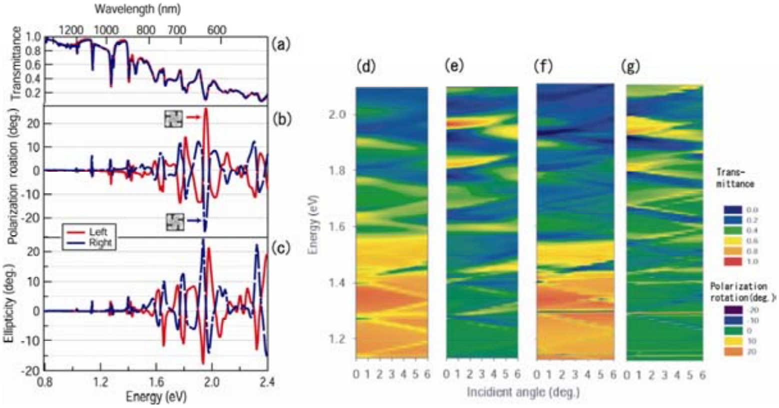

Figure 2. Transmission (a), chirality-induced polarization azimuth rotation (b) and ellipticity (c) spectra at normal incidence. The incident angle dependences of transmittance (d), (f) and chirality-induced azimuth polarization rotation (e), (g) for p-polarized incident light; (d)(e): measurement, (f)(g): calculation.

Figs. 2(d) and (e) show the transmission and polarization rotation spectra of the planar chiral photonic crystal with a left sense of twist measured for p-polarized incident light. We plotted these spectra in the (E, ψ) plane, where E and ψ are the photon energy and angle of incidence, In the transmission spectra, in addition to the waveguide-mode resonances and can also observe intensity modulation caused by Fabry-Pérot interference. However, splitting of the transmission and polarization rotation resonance takes place at a non-zero ψ only in the case of a waveguide mode. This implies that the waveguide modes play a crucial role in the optical activity of dielectric chiral photonic crystal. By identifying the mode numbers of observed resonance we reveled that resonances with larger mode numbers have larger polarization effects. Our experimental finding are reproduced by numerical simulation based on the rigorous diffraction theory.

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Yuri Svirko was born in 1955. In 1978 he graduated Physiucs Department of the M. V. Lomonosov Moscow State University (Moscow, Russia) and in 1982 received PhD in Physics from the same University. In 1986-1994 he was working in General Physics Insitite of the Russian Academy of Sciece on the theory of the nonlinear optical phenomena in condences media. In 1995–1998 Dr Svirko was working at the Department of Physics University of Southampton, UK, on the theory nonlinear polirization effects. In 1998 he joined Gonokami Cooperative Excitation Project of ERATO (University of Tokyo, Japan) and was involved in the invesitgationof the nonlinear excitonic effects in semiconductor nanostrures. From 2001, Dr Svirko holds professorship at the Department of Physics and Mathematics of the University of Joensuu, Finlad. His reseach interests include linear and nonlinear polarization effects in nanostructures and nonlnear optics of nanocarbon materials.

Optical MEMS: From Fiber Telecommunication to Image Display

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Within the Center for International Research on Micro Mechatronics (CIRMM) at IIS, the Univ. of Tokyo, total nine faculty members are working on MEMS (micro electromechanical systems) from fundamental research to their industrial implementation. This article gives an overview about the micro-optical and RF applications of MEMS ongoing in the author's group.

Fiber Optic MEMS: Figure 1 shows the first commercially implemented MEMS device for fiber optic telecom application developed in our lab. The electrostatically controlled MEMS mirror is used in a fiber optic VOA (variable optical attenuator) to regulate optical intensity in the fiber for WDM (wavelength division multiplex) type optical communication. The mirror was controlled by voltage upwards of only 5V and maximum attenuation range of 45 dB was attained. The structure and the process were simplified such that a MEMS foundry service company can mass-produce the MEMS components.

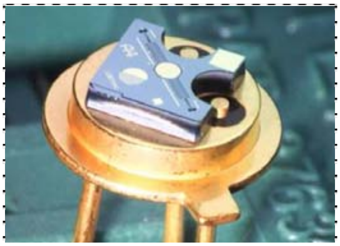

Figure 1. An electrostatically controlled MEMS Micro mirror for the fiber optic variable optical attenuator.

MEMS OCT (optical coherent tomography) Endoscope: As a lateral development of the fiber optic MEMS, we used an electrostatic mirror for a scanning mechanism in a fiber optic endoscope system. The endoscope head shown in Figure 2 is attached at the tail of an optical fiber and scan an infrared of 1.3 microns into a tissue of interest. A reflected light is collected through the same optics and analyzed by using the OCT (optical coherent tomography) interference system to reconstruct the cross sectional image of the tissue under test. Optical resolution of 20 microns and maximum measurement depth of 2 mm were obtained by in vitro test.

Figure 2. OCT fiber optic endscope head using a MEMS scanning mirror.

Flexible Display: Apart from the conventional silicon-based MEMS, we have newly developed a large area MEMS based upon plastic film R2R (roll-to-roll) printing technology in collaboration with VTT Finland. A Fabry-Perot interferometer was constructed by using a pair of plastic PEN films with very thin metal reflector (also as electrode) and an optical interference layer of silicon oxide. Electrostatic operation of films changed the optical cavity length, and the transmissive light changed its color. By preparing three different thicknesses of the optical interference layer, we developed RGB (red, green, and blue) pixels on a single sheet of plastic film. Electronic signage is a target application.

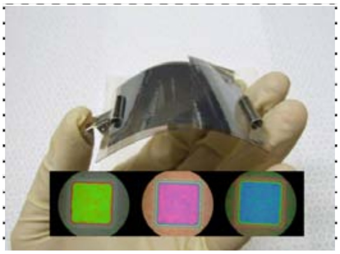

Figure 3. Flexible display sheed based on Fabry-Perot pixels made on plastic films.

Integrated MEMS: The most significant impact of MEMS technologies lie in the integration capability with microelectronics. We have newly developed an integration platform technology for high-voltage (40 V) driver circuit with post-processed MEMS in a single chip. An analog driver CMOS was first fabricated on an SOI (silicon on insulator) wafer with low voltage (5 V) logic circuits. In the same wafer, MEMS mechanical structures were post-processed by using the DRIE process or metal electroplating. This method was also used to integrate different types of MEMS structures in a multi-user multi-chip style.

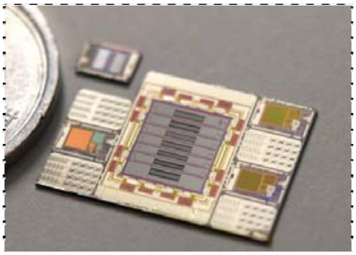

Figure 4. Integrated MEMS with hight-voltage driver CMOS circuits.

RF-MEMS Switch: An RF-MEMS switch was developed by using the SOI DRIE (deep reactive ion etching) micromachining process. The waveguide structures and the microelectromechanical actuators were implemented on the different surfaces of an SOI chip to avoid the mutual electromagnetic interference and to allocate maximum footprint for each structure in a limited are of the chip. A 1.5 mm x 3.2 mm chip for a DPDT (double pole double throw) switch is the minimum record of bulk micromachined RF-MEMS chips ever reported. An array of 4-bit phase shifters used in an APAA (active phased array antenna) is the immediate target application.

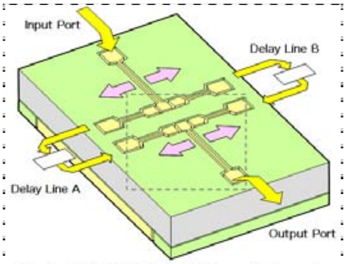

Figure 5. DPDT RF-MEMS switch under development for APAA phase shifter.

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Nanophotonic Structures for Semiconductor Light Sources Fabricated by Nanoimprint Lithography

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We review the activities of the Optoelectronics Research Centre related to compound semiconductor technology, in particular Molecular Beam Epitaxy and soft UV-nanoimprint lithography (UV-NIL). The MBE is used to synthesize nanophotonic III-V heterostructures while the soft UV-NIL is used to fabricate various surface reliefs and components. NIL is an attractive option for low cost mass fabrication of nanopatterns. We combine these two techniques to fabricate narrow line-width laser diodes, nonlinear waveguides and plasmonic devices incorporating metal nanostructures.

Novel III-V semiconductors by MBE

Our MBE activities are focused on developing novel semiconductor material in particular dilute-nitride and antimonide heterostructures. The dilute nitrides (InGaAsN) enable to achieve operation wavelengths at 1.3–1.5 um and demonstrate telecomm lasers with improved temperature behavior or ultra-short pulse operation. The GaSb-based heterostructures are useful for demonstrating narrow linewidth lasers requited in spectroscopy application at 2–3 um wavelengths. We have recently used this material for demonstrating nonlinear semiconductor devices used to generate ultra-short optical pulses.

Narrow linewidth imprinting

We have been developing a novel fabrication method for distributed feedback lasers (DFB-lasers) using corrugated ridge waveguides. Both the waveguide and the DFB-grating are imprinted in a single UV-NIL – step. The nanopatterned waveguides enable single-frequency operation of the laser. Our laser fabrication process is free from regrowth and therefore easily adaptable with various material compositions and emission wavelengths.

An important step in the UV-NIL – process is fabrication of narrow linewidth templates using conventional lithography techniques (e.g. electron beam lithography). We have developed a novel alternative process for these templates. The process is based on a thin-film layer formed on the perimeter of a seed pattern (see Fig. 2a). The linewidth is defined mainly by thickness of the film. The shape of the pattern can be freely defined by the seed pattern. Linewidth of ~20 nm has been fabricated on large areas and transferred on target substrates by UV-NIL.

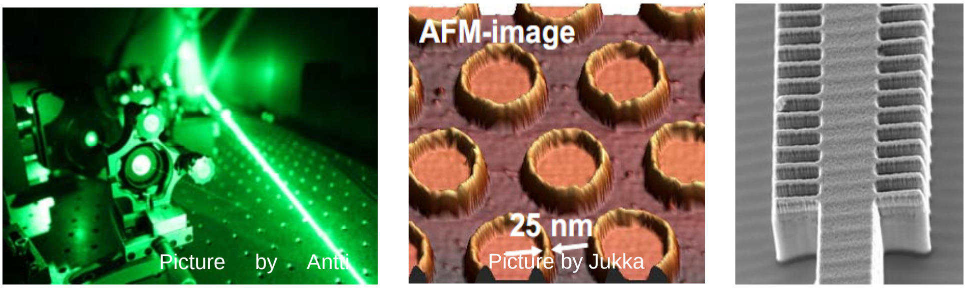

Figure 1. From left to right. a) Green light by SHG of a high power vertical external cavity surface emitting semiconductor laser (VECSEL). b) Narrow linewidth master template for UV-NIL. c) Corrugated ridge waveguide for distributed feedback lasers.

Dr. **Tapio Niemi** received the M. Sc. and Dr. Sci.Tech.) degrees from the Helsinki University of Technology in 1997 and 2002, respectively. He was a visiting researcher at Research Center COM at Technical University of Denmark in 2003–2004. From 2004 he has been a senior researcher at Optoelectronics Research Centre, Tampere University of Technology. His research interests include fabrication and numerical modeling of photonic nanostructures, especially photonic crystals and metallic nanostructures. He has investigated photonic crystal fibers, photonic crystal wavelength division multiplexer and high-Q cavities. He has been setting-up a NIL facility to ORC within “Nanophotonics”- project funded by Tekes (2005–2008). He is currently co-ordinating projects “Localization of light in optical nanocavities (2007–2009, Academy of Finland)”, “Nanophotonics-Extension (2008–2010, Tekes)” and “LENA (2007–2009, Tekes)”. He is also a member of the board (treasurer) of the Finnish optical society.

FDTD Modeling of Micro- and Nano-optical Systems

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When physical size of optical structures shrinks to dimensions smaller than wavelength of incident light, assumptions of scalar and physical optics fail and modeling must be performed according to rigorous diffraction theories based on Maxwell's equations. A versatile modeling method becoming more popular all the time is the finite difference time domain (FDTD) method. FDTD approximates Maxwell's equations in the differential form by a central difference operator in both time and space. The electric and magnetic fields are then represented by their discrete values on the spatial grid, and are advanced in time in steps of Δt. This discrete representation of Maxwell's equations with a properly sampled spatial grid provides reliable numerical solutions for electromagnetic problems ranging from optical frequencies to microwaves.

In modeling of micro- and nano-optical systems, FDTD offers many advantages. A finite computational domain can include dielectric, dispersive, metallic, non-linear, and anisotropic materials. In addition, FDTD takes into account vectorial effects caused by highly confined light beams, and effects of surface plasmon polaritons as well as evanescent waves. In addition, since Yee's algorithm is developed in the time domain, it can propagate pulsed as well as monochromatic electromagnetic fields. Using a wideband time domain pulse, one can solve an electromagnetic scattering problem at multiple frequencies by a single simulation.

We have developed a parallelized FDTD modeling tool that can be run efficiently in parallel processing (cluster-type) computers. We have applied the developed FDTD tool to study super-resolution optical disks [1, 2], light transmission through sub-wavelength apertures [3–5], and light propagation in CMOS-image sensors. Essential results obtained in these simulations and introduction to the FDTD method will be provided in the presentation.

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Juuso Olkkonen received his M.Sc. degree in physics from the University of Oulu, Finland, in 2002. He is currently working as research scientist in Printable electronics and optics center at VTT Technical research centre of Finland. During 2002–2004 he was a visiting scholar in Optical Sciences Center at the University of Arizona. His current research interests are in micro- and nanophotonics, optical biosensors, digital signal processing, and electromagnetic modeling. He has authored and co-authored 16 reviewed journal articles and 13 international reviewed conference papers.

Optical and Electronic Properties of Self-organized Oxide Nanostructures

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Nanostructures such as nanorods, and nanowire find unique applications in electronics, optoelectronics and biosensors due to their high surface to volume ratio, high fraction of chemically similar surface sites and enhanced material characteristics due to quantum confinement effects. Since the first discovery of carbon nanotubes, one-dimensional (1-D) semiconductor materials have attracted extensive interest because of their fundamental importance and wide range of potential applications in nanoscale devices. So far, various types of nano-structured oxide semiconductors have been synthesized by different approaches. Meanwhile, zinc-oxide (ZnO) nanowires have been fabricated by several different processes such as chemical vapor deposition, physical vapor deposition, and molecular beam epitaxy. In these processes, the vapor-liquid-solid (VLS) mechanism is responsible for the nanowire growth, in which a metal or an oxide catalyst is necessary to dissolve feeding source atoms in a molten state initiating the growth of nano-materials. However, there is a rare report on the synthesis of nanostructures by pulsed laser deposition (PLD). In this study, high-oriented ZnO nanowires were found to grow on Al_2O_3 and Si substrates using the laser-assisted VLS technique. From the PL spectra measured at room temperature, a narrow and strong emission peak was observed at 3.3 eV with a very weak deep-level emission, indicating that the nanowires are of high optical quality. Nanowires of various oxide materials such as rare earth-doped ZnO, Fe_3O_4, Ga_2O_3 and $ZnGa_2O_4$ was also successfully fabricated using PLD technique. Optical, magnetic and electronic properties of these nanowires were investigated.

Munetoshi Seki received Ph.D. degrees in physics from Osaka University in 2005. In 2007, he joined the Univ. of Tokyo as an Assistant Professor. His current research interests include the synthesis of oxide nanostructures and artificial superlattices of strong correlated electron systems.

Silicon Photonics

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This paper summarises the work carried out by VTT in Micronova in the field of silicon photonics, which has gained a lot of recent interest [1]. The entire R&D path is explained, including simulations, script-based mask design, wafel-level processing, hyrid integration, packaging and device characterisation. The main focus is on single-moded (SM) waveguides realised in 2−10 µm thick silicon-on-insulator (SOI), but also some nanoscale structures are presented. Target applications are mainly related to telecom, datacom and sensing.

Examples of the basic optical components developed at VTT are low-loss SM waveguides, miniaturised bends [2], waveguide mirrors, different types of passive power splitters and combiners [3], (world's fastest) thermo-optical switches [4], wavelength filters and wavelength (de)multiplexers (Fig. 1).

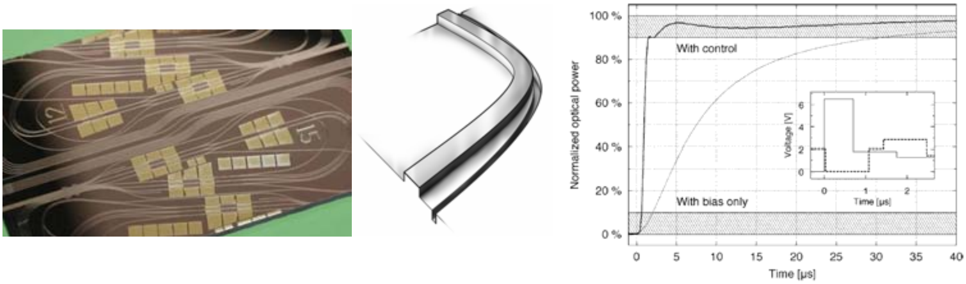

Figure 1. Photonic integrated circuit on SOI (left), including groove bends (middle) and fast thermo optic switches. With differential modulation the switches can be operated with sub-µs response times (right).

An example of nanophotonics integration is capillary driven self-assembly (CDSA) that has been used to realise colloidal crystals on a µm-scale SOI waveguide platform. A capillary network was used to drive colloidal microspheres into the desired crystallization sites, whereas the self-assembly process was based on controlled solvent evaporation [5] (Fig. 2).

Active devices, such as lasers, amplifiers, fast modulators, detectors and electronic ICs are flip-chip integrated on SOI by applying thermo compression bonding [6, 7] (Fig. 3). This is proven to be a simple, accurate and realiable integration method that could also be used to integrate small nanophotonic chips of high-performance on a low-cost SOI platform.

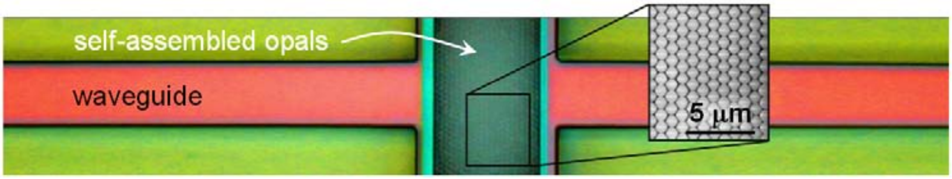

Figure 2. Crystalline silica opal (thickness 10 µm, length 20 µm) interposed between two single mode waveguides on an SOI chip.

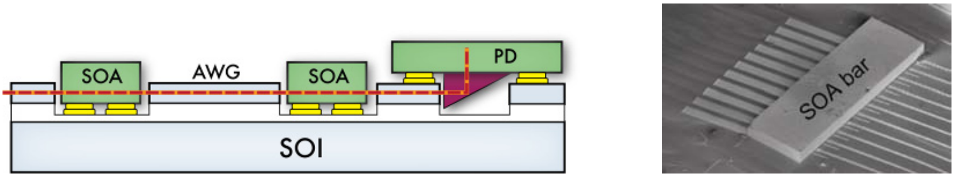

Figure 3. Schematic view of a hybrid integration concept based on thermo compression bondign (left). InP bar with 11 semiconductor optical amplifiers (SOA) flip-chipped on SOI (right).

The integration of active and passive chips into optical modules is obtained by implementing wafer-level DC/RF lines, fiber pigtailing and hermetic sealing. A vision is presented for reducing the packaging costs by using silicon-based packaging concepts.

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Dr **Timo Aalto** is the pioneer of silicon photonics in Finland. He has studed the topic since 1997 when he started at VTT. The results have been published in several master's and doctoral theses prepared in his Photonics and microfluidics team at VTT and submitted to the Helsinki University of Technology. He has also published 11 scientific papers and 25 conference/workshop presentations (5 invited), and filed 8 patent applications (5 patents granted).

Fabrication of Micro and Nano-photonics Devices Based on UV-curable Polymers

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Polymers are considered attractive materials in photonics applications because of their good optical properties and their processability on various platforms. High quality is required, especially, in planar waveguide components. This sets in turn strict demands for the fabrication processes. 1) photolithography and 2) imprinting fabrication of micro- and nano-photonics devices based on UV-curable polymers is evaluated in this work. Conventional shadow-mask UV-lithography can be used to pattern micron-scale structures uniformly over large areas, whereas nanoimprinting enables patterning of nanoscale features, which can also be tilted or round-shaped. Also, 3) the combination of the nanoimprinting and photolithography to effectively utilize the advantages of both patterning techniques simultaneously is studied.

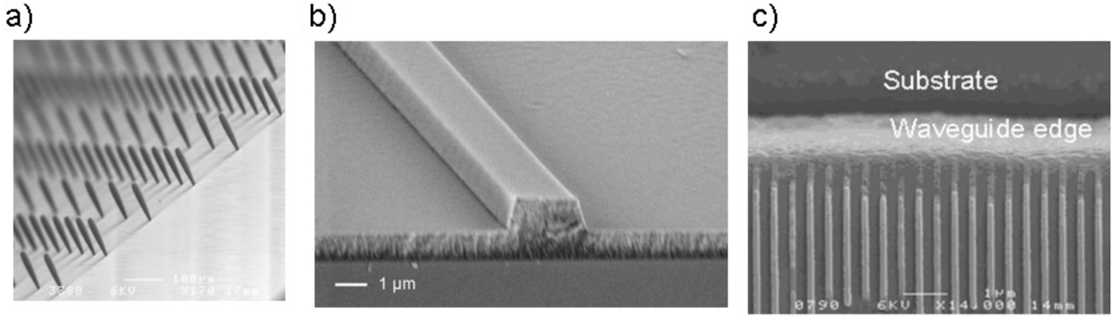

Figure 1. Example structures fabricated with different methods: a) lithographically patterned vertical light coupler (height of 100 µm) array, b) cross section of imprinted 2 µm ridge waveguide and c) top view from the imprinted grating of 400 nm period on lithographically patterned waveguide.

Fig 1. illustrates examples of optical devices that are fabricated with different methods. All the structures are based on UV-curable Ormocer hybrid polymer. Fig 1. a) shows vertical light couplers of 100 µm height that were fabricated by shadow mask lithography. In this case, exposed pillars are UV-cured and unexposed areas are removed by solvent. Single-mode ridge waveguide in Fig 1. b) was patterned by imprinting method. Stamp including grooves was pressed against soft polymer layer and UV-light was applied through the waveguide substrate to pattern the guiding structures. Using the combined lithography/imprinting method mentioned above, gratings on top of a waveguide were fabricated to demonstrate the feasibility of the combined processing scheme. In this method, moulds include both the 3D-structures (e.g. gratings), for imprinting and shadow patterns (e.g. waveguides) for defining the curing area. Replicated binary grating with a period of 400 nm on top of a waveguide is shown in Fig. 1 c).

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"Green MEMS": An Autonomously Moving Micro Robot with Cutting Edge MEMS Technology

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Emerging semiconductor devices such as Micro (and Nano) Electro Mechanical Systems (MEMS) are believed to be a breakthrough for VLSI to open the door to new application fields. Through the last decade, a variety of micro and nano structures appeared together with fabrication process technology. The author's joint research group "TeamMEMS" tries to participate the advancement in both technology and application devices. TeamMEMS aims at conducting application oriented top-down research which would need technology breakthrough and brand-new micro/nano devices developed by the team (technology-oriented).

The top-down research looks forward to provide the "Engineered Nature"; the team does not intend to just copy how nature works in implementation level, but to realize with cutting-edge technologies what nature is aiming at in highly-functional level. Recent top-down activities include autonomous distributed mobile robot: "Pond Skater". A tiny silicon chip floats over water surface, and moves by bubble droplet handling by the integrated low-voltage Electro Wetting on Dielectrics (EWOD).

The technology-driven research tries to develop a competent technology in a worldwide level. Deep Reactive Ion Etching (DRIE) is one of the key technologies of the team. Typical device dimensions of etched out trench available at VDEC's Takeda Super Cleanroom by TeamMEMS go down to 100 nanometres in width and 10 microns in depth. Having such a narrow feature size, the silicon structure not just works as mechanical structure but is able to produce other physical effects. Also, the clear advantage that did not exist before the DRIE is that one can now begin to use also the vertical as an “active device surface”. TeamMEMS has been exploiting the use of vertical wall and is successful in showing the applicability of the in-plane deep P-N junction fabricated on such narrow trenches. It can realize interesting optoelectrical devices such as polarization sensitive optical detector.

A. Minature Pondskating Robot

Realisation of a millimetre scale pond skating device presents many challenges, mainly related to weight considerations, which must be such that the resulting system floats using surface tension effects. Clearly, the weight of any power source is an issue and a successful device needs to minimise (or eliminate) such components. In order to account for scaling effects, the method of propulsion should preferably exclude moving mechanisms, as well as having low power requirements. The team is trying to solve the issues by LSI-MEMS integration technology. The proposed solution is pond skating device by surface tension modification using EWOD. The team has an access to the world’s lowest driving voltage (less than 15V) CMOS post-process compatible EWOD technology developed at the University of Edinburgh. Currently the team is successful in chip floating and one-shot propulsion using wired and wireless power feeding (Fig. 1).

B. Deep Submicron Trench Photodiodes

Taking advantage of recent DRIE technology, TeamMEMS can fabricate silicon structures having feature size down to 100 nanometers, which is smaller than wavelength of visible light. These silicon structures are therefore applicable to optical devices. The authors are proposing to integrate “electrical” devices furthermore, to the nano optical structures. One application device fabricated is a polarization-transmissive thin film (PTTF) solar cell comprising Si photodiode nanowire-grid. This device applied a well-known wiregrid polarizer theory and achieved an extinction-ratio of 4 for transmitted light power as a polarizer. Phodiode was integrated for energy recovery when used as LCD polarizer for mobile environment. Another device is polarization sensitive a surface corrugated p-n junction (Fig. 2) that has a higher polarization dependence of the photocurrent (up to 1:20) and lower leakage current (reduced by factor of 250).

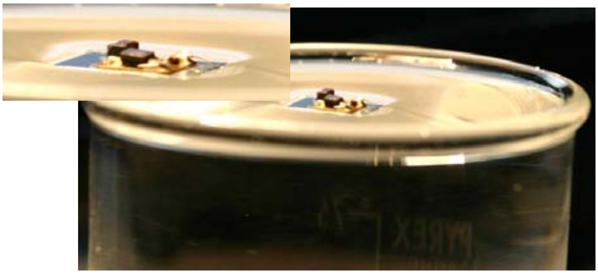

Figure 1. Floating Artificial Pond Skater.

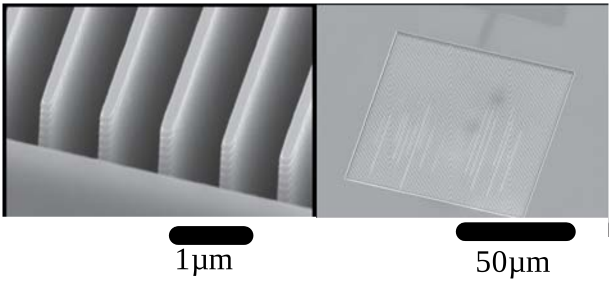

Figure 2. Polarization-sensitive photosensor.

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Crystal Growth Technology for the Integration of Multiple Materials and Functions

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One of the future directions of the development of semiconductor devices is the integration of multiple functions, such as the incorporation of photonic devices, sensors and actuators into Si integrated circuits. This necessitates the integration of different materials and structures. Integration of different materials is, therefore, an essential issue for crystal growth. This paper provides examples of such integration by means of metalorganic vapor phase epitaxy (MOVPE), which is suitable for commercial production of high-quality crystal layers.

The first example is the hetero-epitaxial growth of InGaAs layers on a Si substrate. This is a promising technique to introduce high-mobility electron channels by III-V compound semiconductors into Si LSIs. By the use of selective area growth on an narrow channel and lateral overgrowth, we have obtained InGaAs epitaxial layers on a Si (111) surface without threading dislocations as shown in Fig. 1 [1, 2].

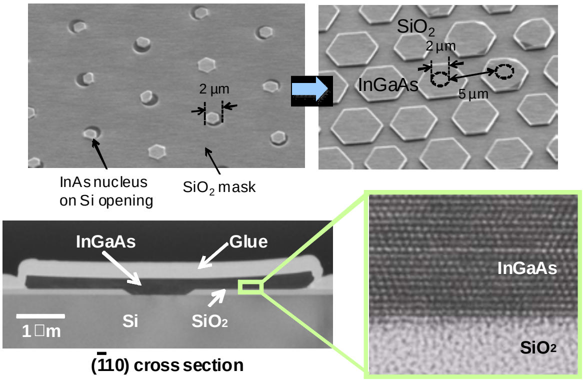

Figure 1. InGaAs epitaxial layers selectively grown on a Si (111) substrate patterned by SiO$_2$. (Up) Bird's views of initial InAs nuclei and laterally-grown InGaAs microdiscs. (Low) Cross-sectional TEM images of the microdiscs.

The second example is the lateral integration of multiple bandgaps by selective-area growth. If we grow multiple quantum well (MQW) structures on a substrate with a mask pattern by SiO$_2$, we can modulate the growth rate in the vicinity of the mask depending on the mask width. Since the modulated growth rate results in the tailored width of quantum wells, we can locally modulate quantum energy levels, allowing us to integrate multiple bandgaps [3].

Using the bandgap integration by the selective-area growth, for $In_{1-x}Ga_xAs_yP_{1-y}$ system, we have fabricated a 4-channel distributed feedback (DFB) laser integrated on a single InP chip [4]. We are currently trying to extend this method to multi-color integrated LEDs as shown in Fig. 2. As a basic step for that purpose, we have systematically investigated the shift of cathode-luminescence wavelength from InGaN / GaN MQWs due to both mask width and position from the mask edge. Such a trend is well explained in terms of the balance between the gas-phase diffusion and the surface incorporation of the precursor of InN and GaN [5], allowing us theoretical design of mask patterns for integrated multi-color LEDs. Based on such principle, we successfully modulated the color of fluorescence due to mask width as shown in Fig. 4, which will finally lead to multiple-color micro LEDs covering visible wavelength range.

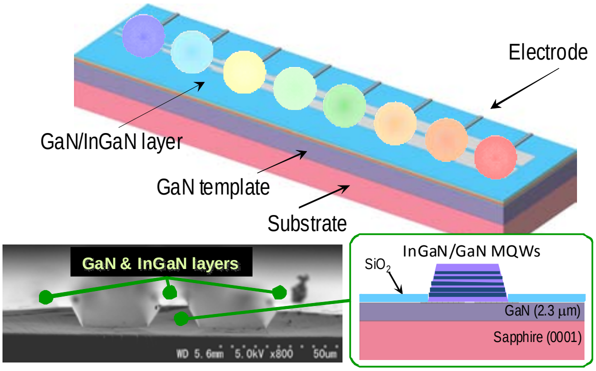

Figure 2. Integrated multi-color LEDs by the selective-area growth of InGaN/GaN multiple quantum wells.

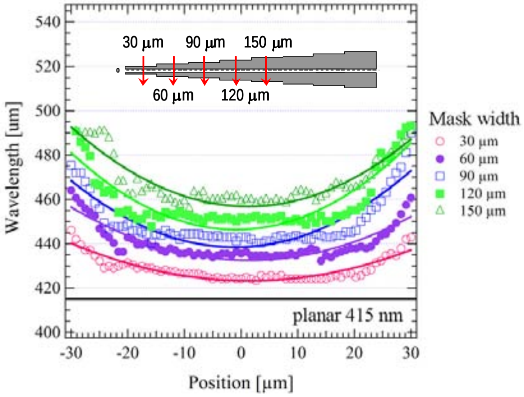

Figure 3. Shift of cathode-luminescence wavelength due to mask width and position from the mask edge.

Figure 4. A fluorescence microscope image of InGaN/GaN MQWs grown on the test mask pattern with stepwise increase of mask width.

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Semiconductor Integrated Optical Switch for Future Photonic Networks

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Integrated photonic switch fabric with nanosecond reconfiguration time and broad operating bandwidth is of particular interest for the future ultra-high-capacity optical-packet-switching (OPS) and optical interconnection networks [1]. Among others, monolithically integrated III-V semiconductor switches are especially attractive owing to the small footprint, low power consumption, and integrability with other active devices. Conventional 1×*N* switches based on broadcast-and-select schemes or cascaded architecture of 1×2 switches, however, suffered from accumulation of noise and/or optical loss with increasing number of port *N*, which have strictly limited the scalability of these approaches.

We have recently proposed and demonstrated a novel type of monolithically integrated InP/InGaAsP 1×*N* switch based on optical phased array [2, 3]. As shown schematically in Fig. 1, dynamic switching is achieved by using arrayed phase shifters to control the optical interference pattern at the output plane of the second slab region. Since the number of modulating stage does not increase with *N*, it offers a potential advantage over the conventional schemes in terms of scalability. Following the first proof-of-concept 1×5 switch [2], we have successfully fabricated and demonstrated a polarization-insensitive 1×8 switch [4] and a large-scale 1×16 switch (Fig. 2) [5]. With the optimized design of array structure and phase modulators, we obtained wideband switching, covering the entire telecommunication spectral band (1520–1580 nm), with low polarization sensitivity and nanoseconds response time. The applicability of our switch to

320-Gbps (40-Gbps × 8λ) broadband wavelength-multiplexed OPS has also been demonstrated experimentally (Fig. 3) [6].

In this talk, I will review our recent progresses and discuss the potential advantages and challenges in realizing large-scale high-speed optical switching circuits on chip.

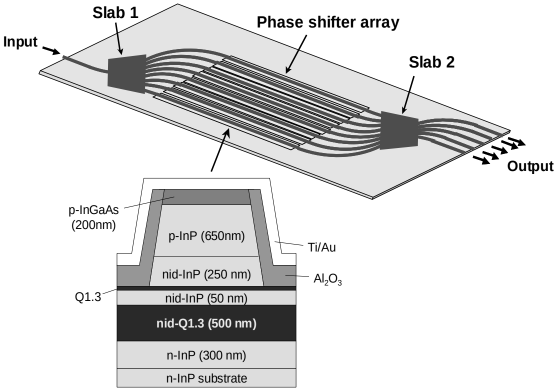

Figure 1. Schematic of 1×N InP/InGaAsP optical phased-array switch.

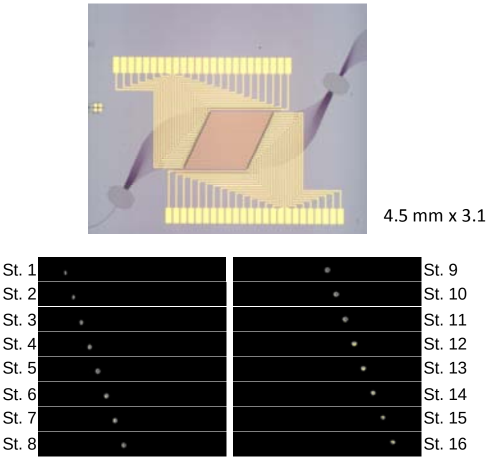

Figure 2. Photograph (top) and observed switching operation (bottom) of 1×16 phased-array InP/InGaAsP switch.

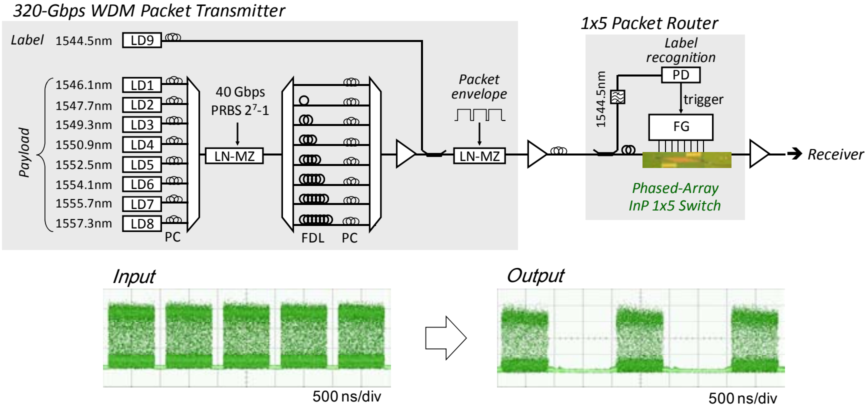

Figure. 3. Experimental demonstration of 320-Gb/s OPS using 1×5 InP phased-array switch.

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Overview of Research in Photonics Group at Helsinki University of Technology

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Photodarkening in ytterbium-doped fibers

Photodarkening in ytterbium-doped fibers appears as time-dependent broadband loss centered at the visible wavelengths with the tail of the loss extending to the IR wavelengths [1], see Fig.1. As such, it poses a threat to the reliability of high-power fiber lasers and amplifiers based on ytterbium-doped fiber technology. Photodarkening effect has been related to the formation of color centers, with higher inversion resulting in faster photodarkening. Inversion-dependent kinetics of this color center formation process has been studied in detail, resulting in derivation of photodarkening rate dependence on the number of excited ytterbium ions [2]. The reverse process, thermal bleaching of photodarkening, has been studied in an effort to identify the underlying darkening and bleaching mechanisms [3]. Complete thermal recovery of a sample to pre-photodarkened state also allows repeated thermodynamic/kinetic measurements to be made on one undisturbed sample, therefore improving the accuracy of the results [4]. Finally, inversion-dependence of photodarkening has been experimentally shown to result in mode-induced transverse photodarkening loss variations, which may influence the fiber laser beam quality with progressing photodarkening [5].

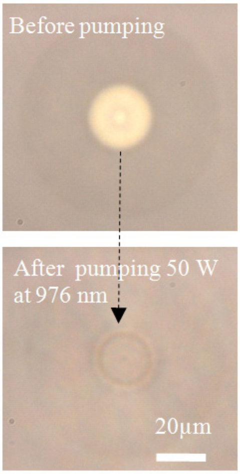

Figure 1. Photodarkening effect in an ytterbium-doped fiber.

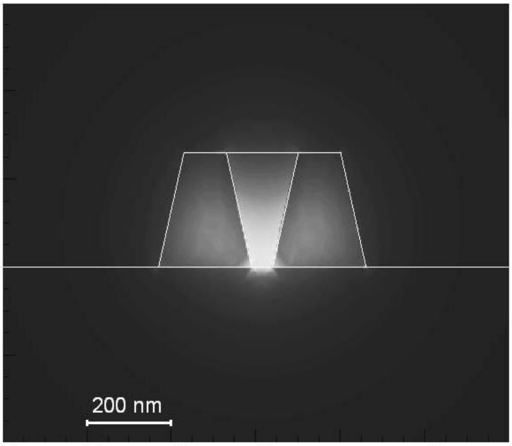

Figure 2. Simulated mode field in a slot waveguide with angled slot sidewalls.

Silicon-on-insulator nanowaveguides

We have studied silicon-on-insulator (SOI) technology for optical guided-wave nanostructures, including photonic crystals. Very tight confinement of light can be achieved in a nanoscale low-index slot on silicon waveguide. Our research on slot waveguides concentrates on targeting optical signal processing based on integrating highly nonlinear materials in slot waveguides [6]. Other potential applications, using different materials to fill the slot, are for example magneto-optic devices and sensors.

In fabrication of slot waveguides, two main challenges are lithographical patterning of the slot structures and filling the slots. Patterning can be done by e-beam lithography or by nanoimprint lithography, followed by reactive ion etching. In modeling and design, the resulting angled sidewalls of the slot need to be taken into account, Fig. 2. shows that enhanced confinement can then be achieved also in vertical direction. Atomic layer deposition (ALD) technique has proven to enable conformal filling of structures that resemble slot waveguides. ALD is also applicable to a wide variety of materials. In addition, angled sidewalls make complete filling easier. We have also designed efficient coupling structures between SOI strip and slot waveguides.

Silver nanoparticle patterns embedded in glass by ion exchange process

Synthesis of silver nanoclusters has been studied, utilizing the ion exchange technique and intentionally enhancing the nanoparticle generation to fabricate patterned Ag nanoparticle formations embedded in glass without any post processing [7]. Our particular target for this work is to develop methods to use localized patterns of nanoparticles for high-sensitivity surface enhanced spectroscopy. Excitation of surface plasmon resonances in Ag nanoparticles leads to strong local field enhancements, thus nanoparticles act as antennas enhancing the coupling of excitation light to sensing molecules and also emission from fluorescence or Raman scattering molecules into free space. Aluminum films on borosilicate glass substrates (Corning 0211) were photolithographically patterned, and substrates were then ion-exchanged in a molten mixture of 5% AgNO3 in a 50/50 mixture of KNO3 and NaNO3 at 300 °C, to produce patterned Ag nanoparticle formations. To observe the cross-sectional distribution of silver nanoparticles, a site-selective focused ion beam (FIB) milling technique was employed for preparing a transmission electron microscopy (TEM) specimen. A bright field TEM image of silver nanoparticles and their electron diffraction pattern are shown in Fig. 3(a). The average size of the particles is estimated to be 5 to 10 nm, and some of them aggregate together to form larger clusters. Fig. 3(b) shows the TEM image of the cross-section underneath the mask edge of a 10-µm circular opening. X-ray energy dispersive spectroscopy gives the element analysis from the sample in Fig. 3(c). During the process, there is a complex distribution of electric field due to the presence of electrochemical potentials between melt, glass and Al mask, and further affected by the conducting mask and diffusion of charged ions. This is thought to explain that highest concentration of Ag particles is some 50 to 100 nm below the mask, near its edge.

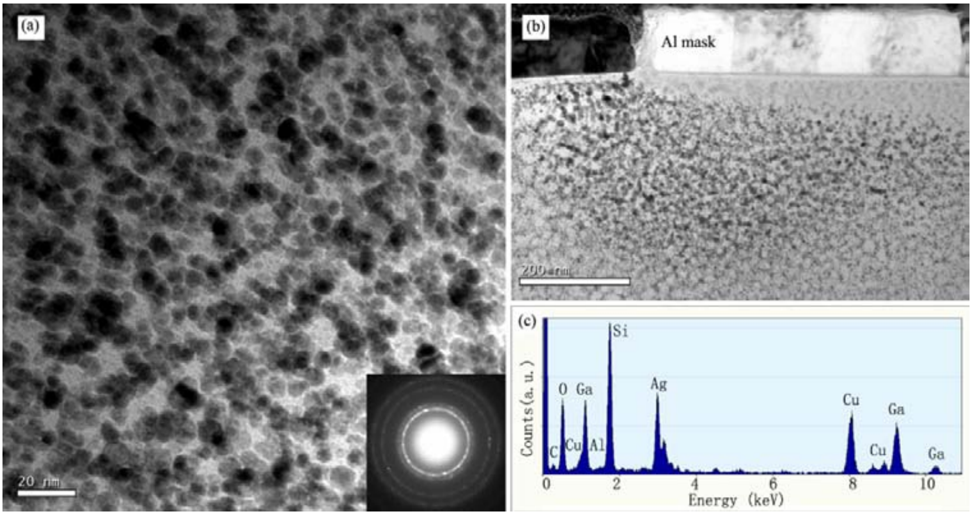

Figure 3. (a) A bright field TEM image of silver nanoparticles and their electron diffraction pattern; (b) TEM image of the cross-section underneath the mask edge of a 10-µm circular opening; (c) element analysis from the sample by X-ray energy dispersive spectroscopy.

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System Architectures in Nanophotonics for Information and Communications Applications

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Recent advances in nanophotonics and sub-wavelength-precision fabrication technology allow the design of optical devices and systems at densities beyond those conventionally limited by the diffraction of light. Such higher integration density, however, is only one of the benefits of nanophotonics over conventional optics and electronics. From a system architectural perspective, nanophotonics drastically changes the fundamental design rules of functional optical systems, and suitable architectures may be built to exploit this. As a result, it also gives qualitatively strong impacts on various systems including information and communications applications [1]. In this talk, two kinds of system architectures will be demonstrated that exploit unique physical processes in light-matter interactions in the nanometer-scale. One is based on optical excitation transfer via optical near-field interactions [2], and the other is based on their hierarchical properties [3].

Firstly, optical excitation transfer are briefly reviewed from a signal transfer perspective and its enabling architectures will be discussed, such as memory-based architecture in which any functionality or computations are associated with table lookup operations [2]. The fundamental processes, such as summation and broadcast of signals, are demonstrated based on geometry-controlled quantum dots and inter-dot interactions via optical near-fields [4, 5]. Also, we show that such systems exhibit higher tamper resistance, or high security, compared with conventional devices by analyzing the physical scale associated with the required energy dissipation [6].

Secondly, we focus on the hierarchical properties in optical near-field interactions. Optical near-fields behave differently depending on the physical scales involved [1, 3]. They have been applied to various applications such as information and communications devices and systems [1,7] and nano-fabrications [8]. Technological vehicles for such architectures include shape-engineered nanostructures [7], quantum nanostructures [9], and many others. Those hierarchical architecture will be useful for solving interconnection bottlenecks between nanoscale devices and macro-scale systems [2], retrieving information from high-capacity, high-density data storage [10], and security-related applications such as traceability [7], authentication [11], anticounterfeit [12].

Through those architectural and physical insights, nanophotonic information and communications systems will be demonstrated that overcome the integration-density limit imposed by the diffraction of light as well as providing unique functionalities which are only achievable using optical near-field interactions.

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Title

Finland–Japan Workshop on Nanophotonics and Related Technologies

Abstract

Nanophotonics is the combination of Photonics and Nanotechnologies, study of the behaviour of light on the nanometer scale and interaction of light with particles or substances at deeply sub-wavelength scale. The benefit of nanophotonics is new functionalities for systems. Functionalities obtained with nanophotonics can be utilized in several fields: optical communications, information processing, data storage, displays, user interfaces, lighting and sensors. In order to estimate the performance and characteristics of the system, the modeling is the first step. In order to be able to utilize the novel functionalities in real systems, the structures need to be fabricated and the performance of the device needs to be verified experimentally. In the fabrication phase, the tailoring of conventional fabrication processes and development of totally new processing technologies needs to be assessed. The nanophotonics research and development needs multidisciplinary approach. The proceedings of the Finland–Japan Symposium covers an overview on latest research activities on the field of nanophotonics and related technologies in Finland and Japan. The symposium is jointly organized by VTT, the Secure-Life Electronics, Global Center-of-Excellence (GCOE) Program of the University of Tokyo and the Nanophotonics Research Center of the University of Tokyo.

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VTT SYMPOSIUM 255 FINLAND–JAPAN WORKSHOP ON NANOPHOTONICS AND RELATED TECHNOLOGIES

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