様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

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研究課題名（和文）Monolithic on-chip waveguide-integrated plasmonic nanolaser

研究課題名（英文）Monolithic on-chip waveguide-integrated plasmonic nanolaser

研究代表者
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研究成果の概要（和文）：ナノ光源を達成するために、近年、プラズモナノワイヤレーザが開発された。ナノワイヤレーザは、実用性に関する重大な課題を抱えている。ナノワイヤのための生成技術は、高品質なレーザー媒質を必要とする。また、ナノワイヤは、トランスファーと精細なアライメントを行わなければ、光回路に集積することができない。
非移動型のナノレーザを実現する有望な方法は、チップ上に直接加工して、特定の形状でアライメントを実現することである。本プロジェクトでは、モノリシックに作られたプラズモナノレーザが実証され、それはオンチップデバイスの製造要件に適合したものになっている。このナノレーザは、低閾値のレーザ発振を実現している。

研究成果の学術的意義や社会的意義
This on-chip plasmonic nanolaser is based on the well-established top-down fabrication technique for semiconductor industry. It opens a new window for next-generation photonic integrated circuits as ultra-small, ultra-fast, low-energy consumption, and high-data-capacity devices at a nanometer scale.

研究成果の概要（英文）：To achieve nanometer-scale light sources, plasmonic nanowire lasers have been prepared in recent years. However, plasmonic nanowire lasers have critical issues on their practicability. The specialized material grown techniques for nanowires, that is, the high-quality lasing gain media, are required, and also these nanowire lasers cannot be integrated with optical circuits on a chip without the transfer process and ultra-fine alignment. A promising way to realize the non-transfer nanolaser is to fabricate them by top-down process directly on the chip with the well-defined geometry and good alignment. In this project, we demonstrated a monolithically fabricated plasmonic nanolaser compatible with the fabrication requirements of on-chip circuits. The nanolaser is designed with a plasmonic metal layer on the top of the laser cavity, providing highly efficient energy transfer between photons, excitons, and plasmons, and achieving UV lasing up to 330 K with a low lasing threshold.

研究分野：ナノフォトニクス

キーワード：Plasmonics　Nanolaser　Nanofabrication　プラズモニクス　ナノレーザー　ナノ加工

様　式　C－１９、F－１９－１、Z－１９（共通）

１．研究開始当初の背景

Photonic integrated circuits (PICs) are promising devices for use as optical nano-processing units and memories that can overcome the bottleneck in the speed of electronic devices, which results from the electrical connections between components. To use light as a data carrier, PICs contain lasers as coherent light sources, optical waveguides to guide the optical signals to their destinations, and photodetectors. Due to the nature of light, PICs can be designed as ultra-fast, ultra-small, low-energy-consumption, and high-data-capacity integrated devices at a nanometer scale.

The main challenges in realizing a functional PIC are the necessity for a nanometer-scale laser and the integration of nanolasers in the device. Semiconducting nanowires were first used with photonic modes in small scale lasers [1], but the sizes of the lasers could not be decreased below the diffraction limit (about half of the wavelength). That is, the laser light could not be confined to subwavelength nanowires. Plasmonic nanolaser devices based on nanowires that overcome this limitation by using surface plasmons to confine light to the interface between metallic films and nanowires, achieving smaller sub-wavelength lasing, have been reported [2-4]. A major disadvantage of plasmonic nanowire nanolasers, however, is the nanowires, used in most nanolaser cavities, are synthesized by bottom-up techniques and not amenable to the production of on-chip and integrated devices. When the nanowires are transferred to the device chip, the nanowire lasers cannot be efficiently coupled to other optical components due to the random orientation, size, and position of the nanowires, which prevents practical integration on a chip.

[1] P. Yang et al., *Science* 292 (2001) 1897
[2] M. A. Noginov, et al., *Nature* 460 (2009) 1110
[3] X. Zhang et al., *Nature* 461 (2009) 629
[4] R. F. Oulton et al., *Nature Physics*, 10 (2014) 870

２．研究の目的

A promising way to realize the on-chip nanolaser is to monolithically fabricate them on one chip, with the controllable geometry, process, and most importantly optical mode. We demonstrate a non-transfer and monolithically fabricated on-chip waveguide nanolaser that has a very low lasing threshold. In this work, the nanolaser can be fabricated monolithically – directly on a chip – using top-down techniques and having the same geometry and are well-aligned on the chip.

３．研究の方法

On-chip fabrication of plasmonic-waveguide nanolaser (Figure 1)

1. ZnO thin film deposition on a sapphire substrate: A ZnO layer with a designed thickness of 120 nm was grown on a sapphire substrate by pulsed laser deposition. The photoluminescence (PL) measurement was performed by a spectrofluorometer (FP-6500, JASCO, Tokyo, Japan). The PL peak shows a bandwidth of 16 nm (Figure 1b).
2. Nanolaser patterns defined by electron beam (EB) lithography: The electron beam resist (ZEP520A, Zeon Corporation, Tokyo, Japan) was spin coated at 5000 rpm with the thickness about 300 nm. The exposure dose of the electron beam system (F7000S-VD02, Advantest, Tokyo, Japan) was set to 110 μC/cm^2. The development was performed under the developer (n-amyl acetate) and rinse (methyl isobutyl ketone and isopropyl alcohol), without a backing process.

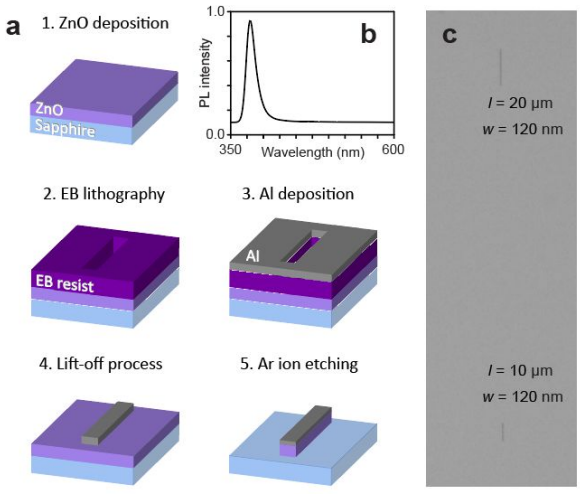

Figure 1. On-chip plasmonic nanolaser fabrication. (a) Fabrication process of the nanolaser. (b) Photoluminescence (PL) measurement of the deposited ZnO on the sapphire substrate. (c) Optical microscopy images of the nanolasers.

3. Al deposition for plasmonic metal: The ion beam deposition system was used for Al deposition. The thickness is set to be 90 nm.
4. Lift-off process to remove the resist with Al top layer: Dimethylacetamide was used as a remover in the lift-off process. The process was done at room temperature.
5. Inductively coupled plasma ion beam etching for ZnO layer: An inductively coupled plasma reactive ion etching system (Ulvac, Inc., CE-300I, Kanagawa, Japan) was used to etch the ZnO layer.

Experimental setup (Figure 2)

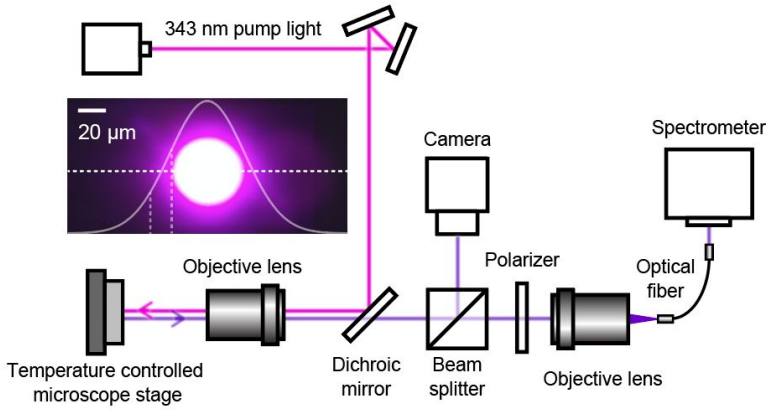

Figure 2. Experimental setup. Experimental setup for the measurement of the nanolaser emission. Inset: Optical microscopy image of the pump light spot incident on the ZnO film without structures.

A femtosecond laser (Orpheus-HP, Light Conversion, Vilnius, Lithuania) as the pump light was utilized. Al mirrors were used to adjust the light path. A dichroic mirror was used to separate the pump light and lasing. A x20 objective lens was used to focus light on the nanocavity. A temperature controlled microscope stage (10084L, Linkam Scientific Instruments, Tadworth, UK) was used to analyze the lasing behavior from -130°C to 60°C. A polarizer was used to analyze the lasing polarization. A x10 lens and an optical fiber were used to collect light into the spectrometer (IsoPlane 160, Princeton Instruments, Trenton, USA).

Since the calculation of the pump energy density of the lasing threshold is affected by the pump light spot size, the spot size after the objective lens was estimated by fitting the Gaussian beam distribution with the color level of the CCD camera as shown in the inset of the Figure 2. The diameter of the pump spot size was kept the same in all measurements in this work and was measured to be approximately 40 μm.

４．研究成果

We report the demonstration of a monolithically fabricated ZnO/Al plasmonic on-chip nanolaser without the need for any transfer or manipulation steps. This design (Figure 1), is composed of a plasmonically active metal layer on the top of semiconductor cavity, which is very different from reported plasmonic nanolasers. This work presents two superiorities for key issues in the fabrication of plasmonic nanolasers. First, due to the direct deposition of metal on the semiconductor cavity, the scattering loss at the interface of semiconductor and metal materials is reduced and the effective area of plasmonic lasing mode in the semiconductor gain material is maximized. Second, the metal layer acts as a mask for the top-down nanofabrication process, preventing damage to the semiconductor gain material and the interface between semiconductor and metal. This work presents a single-mode lasing in the UV region up to 330 K (Figure 3).

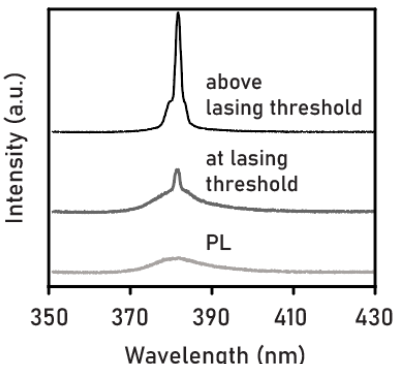

Figure 3. Plasmonic single-mode lasing of the nanolaser at high temperature (330 K). Emission spectra of the monolithically fabricated laser cavity. The spectra are measured at the lasing threshold, together with the spectra below and well above the threshold.

５．主な発表論文等

〔雑誌論文〕　計2件（うち査読付論文　2件／うち国際共著　1件／うちオープンアクセス　0件）

１．著者名 Ho Ya-Lun、Clark J. Kenji、Kamal A. Syazwan A.、Delaunay Jean-Jacques	４．巻 18
２．論文標題 On-Chip Monolithically Fabricated Plasmonic-Waveguide Nanolaser	５．発行年 2018年
３．雑誌名 Nano Letters	６．最初と最後の頁 7769～7776
掲載論文のDOI（デジタルオブジェクト識別子） 10.1021/acs.nanolett.8b03531	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

１．著者名 Deng Chih-Zong、Ho Ya-Lun、Lee Yang-Chun、Wang Zhiyu、Tai Yi-Hsin、Zyskowski Marcin、Daiguji Hirofumi、Delaunay Jean-Jacques	４．巻 115
２．論文標題 Two-pair multilayer Bloch surface wave platform in the near- and mid-infrared regions	５．発行年 2019年
３．雑誌名 Applied Physics Letters	６．最初と最後の頁 091102～091102
掲載論文のDOI（デジタルオブジェクト識別子） 10.1063/1.5101008	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

〔学会発表〕　計2件（うち招待講演　1件／うち国際学会　2件）

１．発表者名 Ho Ya-Lun
２．発表標題 On-chip fabricated non-transfer plasmonic-waveguide nanolaser
３．学会等名 9th International Conference on Surface Plasmon Photonics (SPP9)（国際学会）
４．発表年 2019年

１．発表者名 Delaunay Jean-Jacques、Ho Ya-Lun、Clark J. Kenji、Kamal A. Syazwan A.
２．発表標題 ZnO plasmonic-waveguide nanolaser
３．学会等名 SPIE OPTO（招待講演）（国際学会）
４．発表年 2019年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

Ya-Lun Ho - Google Scholar Citations https://scholar.google.com/citations?user=4r-hkooAAAAJ&hl=en Ya-Lun Ho, Ph.D. / 何 亜倫 - Google Sites https://sites.google.com/site/utyalunho

６．研究組織

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