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研究課題名（英文） On-chip plasmonic nanolasers for ultrafast optical interconnects

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研究成果の概要（和文）：プラズモニクスレーザーは、ナノスケールでのレーザー源として有望である。現在主流である半導体ナノワイヤはボトムアップの技術による合成後、金属表面にトランスファーする方法は、煩雑さによりオンチップデバイスへの実現性が乏しい。本研究では、トランスファー工程が不要なトップダウン技術で製造されるプラズモニクスナノレーザーを実現し、オンチップ回路の製造要件に適応させる。さらに、レーザー利得媒質の上部にあるプラズモニクス金属層を用いる設計により、フォトン‐エキシトン‐プラズモン間のエネルギー交換を効率化し、低発振閾値で330Kまでの紫外線領域におけるレーザー発振を実現した。

研究成果の学術的意義や社会的意義
We propose a nanolaser plasmonic structure with very efficient light confinement at subwavelength dimensions. This nanosize light source circuit can be fabricated on a chip by top-down techniques and therefore offers a means to integrate optical nano-circuits on a large scale.

研究成果の概要（英文）：Due to the demand for photonic computing, on-chip optical communication, and biosensing at the nanoscale, interest in nanolasers has grown. Plasmonic lasers are promising as nanoscale laser sources and have been studied using semiconductor nanowires synthesized by bottom-up techniques and transferred on metal surfaces. The transfer and positioning steps hamper the development of on-chip devices.
We demonstrate a monolithically fabricated plasmonic nanolaser compatible with the fabrication requirements of on-chip circuits. The nanolaser is designed with the plasmonic metal layer on top of the gain medium making top-down nanofabrication of nanolasers and high-quality metal-gain material interfaces possible. This design supports a lasing mode with a large effective area and confines the absorption of the pump light to the area in which the plasmonic-waveguide mode is most intense, thus reducing the lasing threshold. Plasmonic lasing is demonstrated in the ultraviolet region up to 330 K.

研究分野：ナノオプティクス

キーワード：プラズモニクス　光デバイス　ナノ材料

１．研究開始当初の背景

Due to the strong demand for photonic computing, on-chip optical communication, medical imaging, and biosensing at the nanoscale, interest in nanolasers has grown dramatically in recent years. Plasmonic lasers are promising as nanoscale laser sources, and they have been widely studied using semiconductor nanowires on metal surfaces grown by bottom-up techniques.

The first reports on nanolasers used photonic crystals to confine light, but the beam size could not be decreased below the diffraction limit. Plasmonic confinement is more efficient than photonic confinement so that subwavelength lasing has been reported at the interface between metallic films and nanowires (gain medium). Unfortunately, the nanowire plasmonic lasers require transfer and positioning after fabrication, making their use in practical on-chip devices difficult. Furthermore, pure plasmonic modes suffer from ohmic losses in the metal and cannot be efficiently coupled to a waveguide, which prevents on-chip integration.

Our design uses a hybrid plasmonic waveguided mode which confines light at the interface between a top metal layer and a bottom gain medium, as can be seen in Fig 1 left inset (lasing mode). The height of the structure is optimized to obtain maximum confinement at the metal/gain interface. Also, excitation is achieved through the substrate (bottom of the structure) and enables a good overlap of the pump light absorption and the plasmonic mode as well as reduces losses caused by the metal top layer.

Finally, the structure is fabricated by top-down techniques (etching through a mask fabricated by lithography) so that a high density of nanolasers and connection to optical circuits can be fabricated on the same chip.

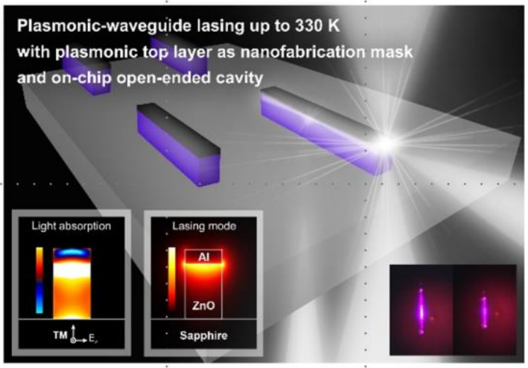

Fig. 1 The on-chip plasmonic nanolaser concept together with simulated light absorption distribution and lasing mode (left insides) and micro photoluminescence images of the fabricated devices (right insides).

２．研究の目的

The general goal is to demonstrate a nanoscale laser source with very high light confinement and small size that can be fabricated using a top-down fabrication technique enabling miniaturization and on-chip integration. High confinement achieved by surface plasmons provides a means to enhance light-matter interaction beyond current limits so that strong field phenomena can be studied and new applications emerge in nonlinear all-optical switching and ultrahigh sensitivity sensing. Also, miniaturization and on-chip integration with electronics due to small size and low power consumption (low lasing threshold) of the nanolasers should make it possible to develop efficient data processing chips that would reduce the huge electricity consumption associated with the rapid growth of digital content (e-commerce, big data, IoT).

The objective is to demonstrate lasing with a structure fabricated by top-down techniques compatible with the fabrication requirements of on-chip circuits without the need for transfer and positioning steps of semiconducting nanostructures. The design of the plasmonic lasing structure should, therefore, enable such a top-down fabrication technique and at the same time achieve efficient excitation of the lasing mode. Finally, lasing at room temperature with a relatively low threshold should be demonstrated.

３．研究の方法

Simulation is used to design the plasmonic structure by analyzing the plasmonic mode characteristics such as the effective mode index, the effective mode area, and the gain threshold. Also, the absorption of the pump light is studied to obtain a good overlap between the plasmonic mode and the pump light absorption. Finally, the cut-off of the different cavity modes (photonic, plasmonic, and its high orders) are investigated to find a means to select the fundamental plasmonic mode. Here, we used the cavity width to select the fundamental plasmonic mode and make sure that the observed lasing originated from the plasmonic mode.

The fabrication technique is briefly described in the following. First, the ZnO gain medium layer is deposited by pulsed laser deposition technique on a sapphire substrate under a well-controlled environment to avoid contamination that is known to be detrimental to efficient light emission in ZnO. After obtaining high-quality ZnO, a resist pattern is fabricated by electron beam lithography and used to deposit the aluminum (Al) top layer of the plasmonic structure. The top Al layer was deposited using ion beam sputtering to guarantee high purity of the metal and also obtain a layer with low roughness. The top Al layer served two purposes, namely, the physical mask for the etching of the plasmonic structure and the top plasmonic metal layer. The thickness of the deposited Al layer is therefore optimized so that after the etching process the remaining Al layer thickness corresponds to the thickness of the Al top layer of the plasmonic structure.

To characterize the emission of the fabricated structure, a micro-photoluminescence setup was built with the possibility to analyze the polarization of the emission (used to confirm the polarization of the excited mode). A tunable pulsed laser was used as the pump light.

４．研究成果

In this report, we demonstrate a monolithically fabricated plasmonic-waveguide-nanolaser (main results published in Nano Letters 18, 7769, 2018). This is the first report showing a non-transfer plasmonic-waveguide nanolaser with a structure size (not only the mode size) in the sub-wavelength regime. A plasmonic waveguided mode capable of sustaining lasing is carefully designed so that top-down fabrication techniques can be used (no need of nanostructure transfer) to simultaneously fabricate the nanolasers together with waveguides for an optical circuit. Particularly, the use of the plasmonic metal layer on top of the gain medium makes it possible for the top-down nanofabrication of well-aligned nanolasers, and at the same time, high-quality metal-gain material interfaces. This provides the key for nanolasers to be integrated with on-chip devices. Moreover, the design supports a lasing mode with a large effective area and confines the absorption of the pump light to the area in which the plasmonic-waveguide mode is most intense, thus reducing the lasing threshold.

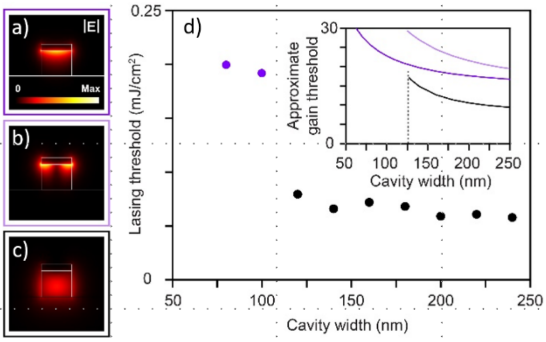

Fig. 2 Description of the plasmonic mode. Mode analysis results for a) the plasmonic mode, b) the higher order plasmonic mode, and c) the photonic mode. d) Plasmonic mode selection by the cavity width.

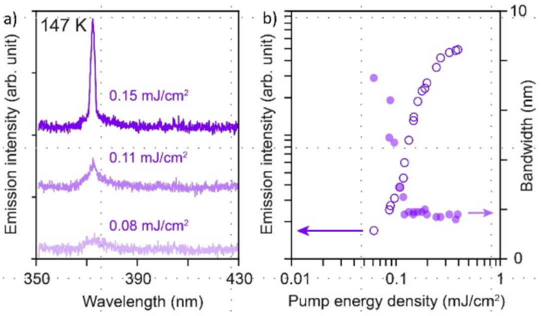

Fig. 3 Lasing threshold and bandwidth analyses at 147 K. a) Emission spectra as a function of excitation power. b) Lasing threshold analysis together with the emission bandwidth.

The plasmonic lasing mode was obtained using ZnO (wide bandgap semiconductor) as the gain medium and aluminum as the metal layer. Due to the use of a wide bandgap material as the gain medium, the demonstration of the plasmonic lasing mode is in the ultraviolet region. Figure 2 shows the results of the mode analysis of the proposed structure. The fundamental plasmonic mode shown in Fig. 2 a) exhibits very high confinement at the interface between the metal and the gain. The higher plasmonic mode shown in Fig. 2 b) is less confined and possesses a cut-off for the cavity width so that it is possible to select the fundamental plasmonic mode using the size of the cavity width. The photonic mode is shown in Fig. 2 c) for comparison purposes and has also a clear cut-off width as shown in Fig. 2 d). To confirm the plasmonic emission, the polarization of the emitted light is recorded as a function of the cavity width. This enables us to distinguish unambiguously the plasmonic mode from the photonic mode. Indeed for the plasmonic mode, the light polarization is along the cavity. In contrast to the photonic mode, the polarization lies in the direction perpendicular to the cavity as can be seen in Fig. 4.

The results for the lasing threshold are shown in Fig. 3 a) and were recorded at 147 K. A non-linear threshold region for lasing is revealed in Fig. 3 b) corresponding to a drastic decrease in the full width at half maximum of the emission. Finally, plasmonic emission near room temperature confirming plasmonic lasing at room temperature is shown in Fig. 5.

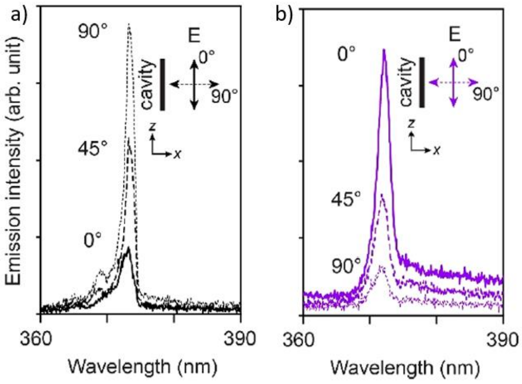

Fig. 4 The polarized emission for a) the photonic mode and b) the plasmonic mode.

To extend the range of the lasing wavelengths for the proposed structure, different materials for the gain medium were investigated. We particularly focused on perovskite materials and developed a technique to fabricate high-quality perovskite structures on a substrate from perovskite nanocrystals. Using this technique, a microring laser with a well-defined photonic mode was demonstrated as a first step. Following this result, different designs for the perovskite-based plasmonic structure have been optimized by simulation and their fabrication is currently on-going.

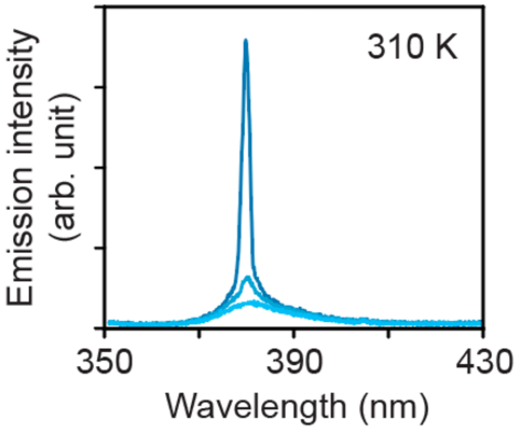

Fig. 5 Emission spectra as a function of excitation power showing lasing near room temperature.

In a view to integrating photodetectors with the proposed plasmonic light source, plasmonic structures realizing light detection with hot electrons were investigated (main results published in Applied Physics Letters 116, 161103, 2020; Nanoscale 11, 17407-17414, 2019; ACS Photonics 5, 2617-2623, 2018). For example, we proposed a structure consisting of Si channels separated by an Au grating with interdigitated Au nano slabs acting as electrodes for near-infrared photodetection and demonstrated photodetection with spectral selectivity in the telecommunications C-band.

5．主な発表論文等

〔雑誌論文〕　計13件（うち査読付論文　13件／うち国際共著　11件／うちオープンアクセス　3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 －

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２．論文標題 Narrowband thermal emission from Tamm plasmons of a modified distributed Bragg reflector	５．発行年 2018年
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３．雑誌名 ACS Photonics	６．最初と最後の頁 2446～2452
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３．雑誌名 Nano Research	６．最初と最後の頁 4323～4332
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１．著者名 Xiao Hongbin、Lo Shu-Cheng、Tai Yi-Hsin、Clark J. Kenji、Ho Ya-Lun、Deng Chih-Zong、Wei Pei-Kuen、Delaunay Jean-Jacques	４．巻 1
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１．発表者名 J.-J. Delaunay, Y.-L. Ho, J. K. Clark, A. Syazwan A. Kamal
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３．学会等名
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(19)Ya-Lun Ho, J. Kenji Clark, A. Syazwan A. Kamal, ○Jean-Jacques Delaunay

２．発表標題
On-chip fabricated non-transfer plasmonic nanolaser

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META 2019（招待講演）（国際学会）

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2019年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

JJ Delaunay's laboratory webpage
http://scale.t.u-tokyo.ac.jp/research/index.html
JJ Delaunay's researchgate page
https://www.researchgate.net/profile/J-J_Delaunay/research
JJ Delaunay's scholar google page
https://scholar.google.co.jp/citations?user=ffxMbFgAAAAJ&hl=en

６．研究組織

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