Extended Abstracts of the 2016 International Conference on Solid State Devices and Materials, Tsukuba, 2016, pp917-918

PS-12-05

Integration of Si nanowire waveguides and magneto-optical plasmonic waveguides on a Si substrate

Vadym Zayets, Hidekazu Saito, and Shinji Yuasa

Spintronics Research Center,
National Institute of Advanced Industrial Science and Technology (AIST),
Umezono 1-1-4, Tsukuba, Ibaraki 305-8568, Japan
Phone: +81-298-61-5426 E-mail: v.zayets@aist.go.jp

Abstract

$Co/TiO_2/SiO_2$ plasmonic waveguide was monolithically integrated with a Si nanowire waveguide on a Si substrate. In order to achieve a low propagation loss and a good coupling efficiency, the wedge and bridge types of plasmonic waveguides were used. Low optical loss in plasmonic waveguide of 0.7 dB/μm and coupling loss of 4 dB per facet are demonstrated.

1. Introduction

The integration of different optical components on one substrate has many benefits. Similar to electronic devices, an integrated optical circuit may have a lower cost and better functionality. The size of MOSFET transistors are very small and millions of the transistors can be integrated into one electrical circuit. In contrast, the size of optical components is not as small. The typical length of optical components is about a millimeter and only a few optical components can be integrated into one cheap. The length of optical components is limited by the wavelength of light. The size of optical elements can be reduced when Si nanowire waveguides or/and plasmonic waveguides are used.

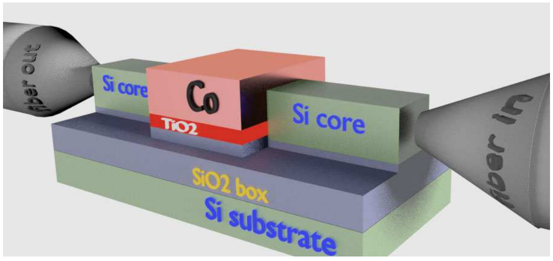

Fig. 1 $Co/TiO_2/SiO_2$ magneto-optical plasmonic waveguide monolithically integrated with Si nanowire waveguide

The optical confinement in a Si nanowire waveguide is strong, because of a high refractive index contrast. Due to strong optical confinement, the Si nanowire waveguides are very narrow with width of 450 nm and they can sharply bend with bending radius as small as 1 μm. Even though the length of Si-nanowire devices has to be still relatively long, by bending the optical device can be packed into small area of a few μm^2.

The optical confinement of a plasmonic waveguide is much stronger that the confinement in the Si nano waveguide, because of a substantially larger refractive index contrast between a metal and a dielectric. The plasmonic devices are even smaller. Typical length of a plasmonic device is 10-30 μm.

Different functionalities can be achieved using either Si nanowire waveguides or plasmonic waveguides. It is attractive to integrate into one cheap both the Si nanowire waveguides and plasmonic waveguides. In this case a small-size cheap with substantial number of optical elements and complex functionality could be fabricated.

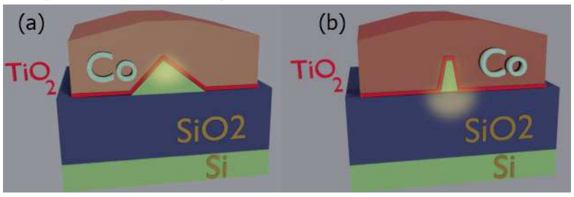

Fig. 2 Cross-section of (a) wedge-type and (b) bridge-type $Co/TiO_2/SiO_2$ plasmonic waveguide. The wedge is a 300-nm-wide Si line, which wet-etched into triangular shape. The width and height of the Si bridge are 70 and 220 nm, correspondingly. The field distribution of plasmon is shown in yellow color.

However, there are several issues to be solved in order to make such dense optical integration to be possible. Firstly, an essential part of any plasmonic waveguide is a metal, which strongly absorbs light. The design of a plasmonic waveguide should be optimized in order to minimize the optical loss. Secondly, the optical distributions in plasmonic and Si waveguides are substantially different. Such mismatch causes a significant coupling loss between plasmonic and Si waveguides. Such coupling loss should be minimized.

2. Magneto-optical plasmonic waveguide

In a case when the metal of a plasmonic waveguide is ferromagnetic, the plasmonic waveguide may have a unique property. It could be transparent in one direction, but it could block light in opposite direction [1]. This function is called the optical isolation. The optical isolator is an important component of optical circuits. Its function is to protect optical elements from unwanted back reflection. In case of a dense optical integration, it is harder to achieve a good optical coupling between elements and the usage of an isolator is essential [2].

A ferromagnetic metal, which has large magneto-optical constants, is an essential material for the isolator. It is known [1-2] that the propagation loss of the surface plasmons in ferromagnetic metals like Fe, Co or Ni is at least an order of magnitude larger than the optical loss of plasmons in Au, Ag and Cu, which are the conventional metals for the plasmonic devices. In case when optical loss is too large, all light is absorbed and the plasmonic device can not function.

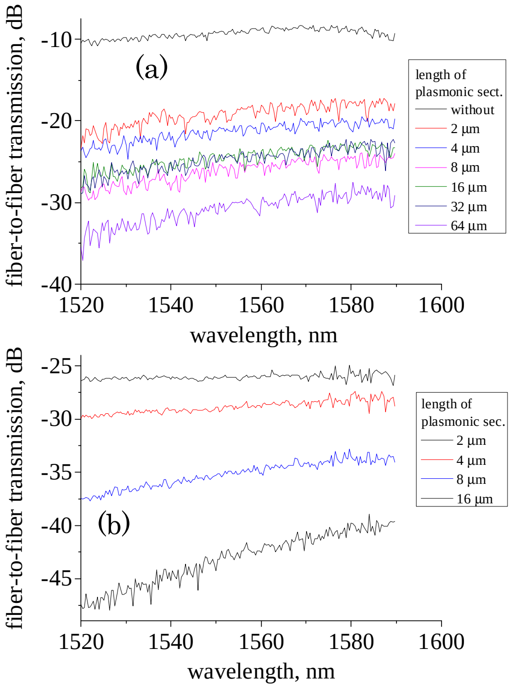

Fig. 3 Fiber-to-fiber transmission of the $Co/TiO_2/SiO_2$ plasmonic structures plasmonic waveguide integrated with a Si nanowire waveguides for different lengths of plasmonic section. (a) bridge-type structure (b) wedge-type structure. The black line in (a) shows the transmission for a Si nanowire waveguide without a plasmonic section.

We have proposed [3-5] a new design of the plasmonic waveguide, which contains two dielectric layers. By optimizing this design, it is possible to reduce significantly the propagation loss and to increase the magneto-optical (MO) figure-of-merit. Using this method, the low propagation loss of 0.17 dB/µm in a Fe/MgO/AlGaAs plasmonic structure fabricated on a GaAs was demonstrated [4].

2. Wedge- and bridge-type plasmonic waveguides

In a case of plasmonic waveguide on GaAs only the usage of optimized double-layer dielectric MgO/AlGaAs was sufficient to achieve sufficiently low optical loss [4]. A Fe stripe was used for in-plane confinement. The case of the integration on Si is different. We have fabricated several $Co/TiO_2/SiO_2$ plasmonic waveguides on Si using Co stripe. Even though double-layer TiO_2/SiO_2 is proved to efficient for loss reduction, the optical loss in plasmonic structure with a Co stripe was unacceptably high about 10-15 dB/µm. The reason of a high loss was found to be the optical scattering at the edges of the metal stripe. In order to integrate a plasmonic waveguide with a Si nanowire waveguide, the metal stripe should be narrow about 450 nm. In the case of a narrow plasmonic waveguide the scattering at metal edges becomes a major mechanism of optical loss. In order to avoid it, another method for in-plane confinement should be used, which could ensure the confinement of a plasmon out of metal edges. Also, the confinement should be such that the optical fields of a plasmon and a waveguide mode are well-matched and a good optical coupling between them could be achieved. We have found that the bridge type and wedge type of in-plane confinement well satisfy both above conditions.

Figure 1 shows the measurement setup. The metal blocks direct propagation of light from input to output fiber. Light can only reach the output when a plasmon is excited at metal interface.

Figure 2 shows the cross-section of bridge and wedge types of plasmonic waveguides. In both cases the Si was used as the wedge and bridge material.

Figure 3 shows measured fiber-to-fiber transmission. The transmission includes the fiber/Si-waveguide, Si-waveguide/plasmon coupling losses and the plasmon propagation loss. By comparing transmission at different lengths of the plasmonic section, the low optical loss of 0.7 and 1 dB/mm was measured for bridge- and wedge-type plasmonic waveguides, respectively. Comparing the transmission for cases with and without plasmonic section, the Si-waveguide/plasmon coupling loss was evaluated to be 4 and 6 dB per facet for bridge- and wedge- types, respectively.

3. Conclusions

The usage of optical in-plane confinement, which remove a plasmon out of metal edge, is essential to fabricate a low-optical-loss magneto-optical plasmonic waveguide integrated with Si nanowire waveguides. We have demonstrated a low optical loss and a good coupling efficiency for both the wedge- and bridge- type $Co/TiO_2/SiO_2$ plasmonic structures.

The experimental study of the isolation effect in the plasmonic waveguides will be discussed at the conference side.

Acknowledgements

Support of Japan Society for the Promotion in Science (Kakenhi) is greatly acknowledged.

References

[1] V. Zayets, H. Saito, S. Yuasa, and K. Ando, Materials **5** (2012) 857.

[2] G. Armelles, A. Cebollada, A. García-Martín, and M. U. González Adv. Optical Mater. **1** (2013)10.

[3] V. Zayets, H. Saito, S. Yuasa, and K. Ando, J. Appl. Phys. **111**, (2012) 023103.

[4] V. Zayets, H. Saito, S. Yuasa, and K. Ando, Opt. Express **23** (2015) 12834.

[5] H. Shimizu, T. Kaihara, S. Umetsu, and M. Hosoda, *Extended Abstracts of Spintronics VIII SPIE meeting* (2015) 9551.