Demonstration of low-loss on-chip integrated plasmonic waveguide based on simple fabrication steps on silicon-on-insulator platform

Tobing, Landobasa Yosef Mario A. L.; Tjahjana, Liliana; Zhang, Dao Hua

2012

Tobing, L. Y. M. A. L., Tjahjana, L., & Zhang, D. H. (2012). Demonstration of low-loss on-chip integrated plasmonic waveguide based on simple fabrication steps on silicon-on-insulator platform. *Applied physics letters*, 101(4), 041117-.

<https://hdl.handle.net/10356/95033>

<https://doi.org/10.1063/1.4739523>

© 2012 American Institute of Physics. This paper was published in *Applied Physics Letters* and is made available as an electronic reprint (preprint) with permission of American Institute of Physics. The paper can be found at the following official DOI: [<http://dx.doi.org/10.1063/1.4739523>]. One print or electronic copy may be made for personal use only. Systematic or multiple reproduction, distribution to multiple locations via electronic or other means, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper is prohibited and is subject to penalties under law.

Downloaded on 26 Apr 2023 20:57:45 SGT

Demonstration of low-loss on-chip integrated plasmonic waveguide based on simple fabrication steps on silicon-on-insulator platform

Landobasa Y. M. Tobing, Liliana Tjahjana, and Dao Hua Zhang

Citation: *Appl. Phys. Lett.* **101**, 041117 (2012); doi: 10.1063/1.4739523

View online: <http://dx.doi.org/10.1063/1.4739523>

View Table of Contents: <http://apl.aip.org/resource/1/APPLAB/v101/i4>

Published by the [American Institute of Physics](#).

Related Articles

Ultra-thin silicon-on-insulator strip waveguides and mode couplers

Appl. Phys. Lett. **101**, 221106 (2012)

Loop-mirror-based slot waveguide refractive index sensor

AIP Advances **2**, 042142 (2012)

Integrated optofluidic index sensor based on self-trapped beams in LiNbO₃

Appl. Phys. Lett. **101**, 181104 (2012)

A quantum dot rolled-up microtube directional coupler

Appl. Phys. Lett. **101**, 171111 (2012)

Terahertz beam focusing based on plasmonic waveguide scattering

Appl. Phys. Lett. **101**, 151116 (2012)

Additional information on *Appl. Phys. Lett.*

Journal Homepage: <http://apl.aip.org/>

Journal Information: http://apl.aip.org/about/about_the_journal

Top downloads: http://apl.aip.org/features/most_downloaded

Information for Authors: <http://apl.aip.org/authors>

ADVERTISEMENT

AIP | Applied Physics
Letters

**EXPLORE WHAT'S
NEW IN APL**

SUBMIT YOUR PAPER NOW!

**SURFACES AND
INTERFACES**

Focusing on physical, chemical, biological, structural, optical, magnetic and electrical properties of surfaces and interfaces, and more...

**ENERGY CONVERSION
AND STORAGE**

Focusing on all aspects of static and dynamic energy conversion, energy storage, photovoltaics, solar fuels, batteries, capacitors, thermoelectrics, and more...

Demonstration of low-loss on-chip integrated plasmonic waveguide based on simple fabrication steps on silicon-on-insulator platform

Landobasa Y. M. Tobing,^{a)} Liliana Tjahjana, and Dao Hua Zhang^{b)}

Nanophotonics Laboratory, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798

(Received 27 May 2012; accepted 13 July 2012; published online 25 July 2012)

We report the experimental realization of a robust silicon-based plasmonic waveguide structure which can theoretically provide sub-wavelength confinement for E_x - and E_y -polarized surface plasmon polariton modes. Our waveguides exhibit propagation loss as low as 0.2 dB/ μm with $\sim 50\%$ coupling efficiency. © 2012 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4739523>]

Surface plasmon polariton (SPP) is a light propagation mode along metal-dielectric interface that is coupled to collective electron plasma oscillations in the metal. On-chip plasmonic waveguides (PWG) have attracted great interest because of its subwavelength light confinement, which can potentially lead to higher device integration density compared to conventional dielectric waveguides.¹ Silicon on insulator (SOI) provides a suitable platform for plasmonics for its large refractive index contrast ($\Delta n \sim 2$) and established deep submicron fabrication process capability.² Experimentally, Si-based on-chip PWGs have been demonstrated for different waveguide geometries and mode excitations.^{3–7}

The most common type of PWG works based on horizontally polarized SPP modes (E_x -polarized), whose structure consists of a narrow silicon waveguide buried inside a thick metal film.^{3–6} The reported propagation losses for this PWG type are in the range of 0.37–0.8 dB/ μm , which are achievable through various loss reduction attempts, e.g., the use of top dielectric spacer layer for SPP-mode isolation from the top metal,³ and the use of waveguide sidewall thermal oxidation give light confinement within the oxide instead of in the silicon core.^{5,6} However, extra fabrication steps are often required to realize such PWG, for example, the use of electroplating to deposit $\sim 1\mu\text{m}$ thick copper in Ref. 5 and the use of Ar ion milling to create deep-submicron trench on 200 nm thick gold film.⁶ Other type of PWG works based on vertically polarized SPP modes (E_y -polarized), where the metal film only covers the silicon waveguide top instead of the whole waveguide.⁷ Since there is no side metal deposition in this PWG structure, a more flexible planar integration is expected, but at the expense of less lateral mode confinement, which may reduce the integration density. In addition, tight alignment between metal overlay and silicon waveguide is necessary to ensure the excitation of E_y -polarized SPP mode. The reported propagation loss for this type is ~ 2 dB/ μm . Note that the structure in Ref. 3 also supports E_y -polarized SPP mode, but generally, the modal confinement is not subwavelength in nature because the metal contributes more as a loading effect. This is similar to the case of rib waveguide in conventional integrated optics, where the mode confinement is characteristically below the waveguide core for small widths (weak loading),

and progressively moving towards the waveguide core at increasing widths (strong loading).

Clearly, there is a trade-off between the above two PWG types. The E_x -polarized PWGs exhibit lower propagation loss at the expense of thick metal cladding and complicated fabrication steps, while the E_y -polarized PWGs require simpler fabrication steps but exhibit higher propagation loss. Indeed, there is a need for a realization of low loss on-chip PWG with subwavelength mode confinement and relatively simple fabrication strategy.

In this Letter, we propose a simple yet robust PWG structure consisting of a silicon waveguide coated by thin metal film (shown in Fig. 1), which is theoretically shown to provide sub-wavelength confinement for both E_x -polarized and E_y -polarized SPP modes, and experimentally shown to have ~ 0.2 dB/ μm propagation loss and $\sim 50\%$ coupling efficiency for E_x -polarized mode.

As shown in Fig. 1, the proposed PWG structure consists of narrow silicon waveguide clad by gold film without top dielectric spacer layer and with metal thickness much smaller than those demonstrated in Refs. 3, 5, and 6. Ideally, semi-infinite metal is required for the realization of metal-insulator-metal plasmonic waveguide. However, realistically this may not be necessary since the extension of plasmonic field is not far from metal-dielectric interface. The SPP field penetration depth in the metal (δ_m) can be calculated by⁸ $\delta_m = (\lambda/2\pi)[(\epsilon'_m + \epsilon_d)/\epsilon_m^2]^{1/2}$, where ϵ_m and ϵ_d are the real permittivities of metal and dielectric, respectively. By

FIG. 1. SEM micrograph of SOIPWG before ZEP coating.

^{a)}Electronic mail: LTOBING@pmail.ntu.edu.sg.^{b)}Electronic mail: EDHZHANG@ntu.edu.sg.

inserting permittivities of silicon ($\epsilon_d = 12.11$), and that of gold⁹ ($\epsilon_{Au} = -96.9 + i10.97$), δ_m is found to be ~ 23 nm (for $\lambda = 1550$ nm). For that reason, the gold thicknesses in this work are fixed at $t_{Au} = 40$ nm. The modal effective indices (n_{eff}) of SOI waveguide (SOIWG) and the proposed PWG (SOIPWG) as a function of waveguide width (W_p) are presented in Fig. 2, where the mode analysis is carried out by finite element method (FEM). One can see that a thin metal is sufficient to confine both quasi-TE (E_x -polarized) and quasi-TM (E_y -polarized) SPP modes.

The dependence of modal effective index on waveguide width is similar to the case of conventional dielectric waveguide, except for the fundamental quasi-TE mode (quasi-TE₀), where the effective index decreases at increasing width. This is because quasi-TE modes are the result of mutual coupling of two E_x -polarized SPP modes at two waveguide sidewalls, which give mode splitting consisting of symmetric and anti-symmetric modes. Here, the symmetric (anti-symmetric) mode corresponds to quasi-TE₀ (quasi-TE₁) modes in Fig. 2. The mode splitting (as defined by the effective index difference between symmetric and anti-symmetric modes) is inversely dependent on the interaction length between two SPP modes (as characterized by waveguide width). Thus, the mode splitting increases at decreasing waveguide width,⁹ and the effective index of both quasi-TE₀ and quasi-TE₁ converges to a single value belonging to that of the uncoupled E_x -polarized SPP mode ($n_{eff} \sim 3$) at increasing waveguide width.

In comparison with TE mode of a typical SOI waveguide (solid line), there is a large index mismatch between the SOIPWG and SOIWG modes, indicating that the coupling efficiency between SOIWG and SOIPWG will always be limited by Fresnel reflection caused by mode index mismatch [$R = (n_{eff,2} - n_{eff,1})^2 / (n_{eff,2} + n_{eff,1})^2$]. More importantly, this remains the case regardless of whether taper structure is employed during coupling or whether there is a total overlap between the mode profiles of SOIWG and PWG. By substituting the effective index for SOIPWG ($n_{eff} \sim 3.1$) and SOIWG ($n_{eff} \sim 2.3$) modes at $W_p = 450$ nm,

FIG. 2. Mode characteristics of quasi-TE and quasi-TM modes of SOIPWG for $t_{Au} = 40$ nm gold thickness. The TE mode of SOIWG is also shown for comparison. The insets show the electric field profiles corresponding to each mode.

the maximum coupling efficiency can be estimated as ~ 0.1 dB/facet.

The device fabrication is outlined in the following steps. First, the SOI photonic waveguides were fabricated by 193 nm DUV lithography,² where the waveguide thickness is 220 nm and the lower oxide cladding is 2 μ m. The device consists of main waveguide (of waveguide width $W_{SOI} = 450$ nm) tapered down at the middle section to narrow waveguide, which has waveguide width (W_p) ranging from 150 nm to 250 nm. The taper length is $L_t = 10$ μ m, while the narrow waveguide length (L_N) varies from 50 μ m to 400 μ m. The focused grating couplers were integrated at both sides as input and output ports, which are 1 mm apart and designed to excite TE mode in SOI waveguide. Second, the SOIWG was then converted to SOIPWG by covering the middle section of the narrow silicon waveguide with gold film at a length of L_P , which is fixed at 10% of the total narrow waveguide length, i.e., $L_P = 0.1L_N$. In this step, electron beam lithography was employed to make the opening before metal deposition, and 5 kV acceleration voltage was chosen to ensure the electron beam penetration depth not exceeding the resist thickness so as to prevent substrate damage. Then, the metal deposition was carried out by e-beam evaporation, where 3 nm thick titanium was used as adhesion layer before 40 nm gold deposition took place. Finally, the samples were spun coated with ZEP520 e-beam resist for isolation. Here, the e-beam resist was preferred to conventional photoresist due to the lower optical absorption. The SEM micrograph of gold coated SOI waveguide before ZEP coating is shown in Fig. 1.

For device measurements, the light is coupled and collected by means of near-vertical coupling mechanism, where the light source and detector used in this work are SANTEC TLS-510 tunable laser and ILX FPM-8210 fiber power meter, respectively. The measurements were carried out before and after metal deposition in order to extract SPP related losses. Here, the fundamental TE mode of SOIWG can only couple to quasi-TE₀ mode in SOIPWG due to different symmetry conditions of quasi-TM₀, which has anti-symmetric E_x profiles. The same reasoning applies for the higher order plasmonic modes, i.e., quasi-TE₁ and quasi-TM₁. The normalized transmission of SOIPWG for different widths (W_p) and lengths (L_p) are presented in Fig. 3(a), where each point corresponds to measurements across 6 samples with standard deviation represented by the error bar. The extraction of both the propagation (α_{SPP} , α_{SOI}) and coupling (η_{SPP} , η_{SOI}) losses are obtained from linear fit, and shown in Fig. 3(b) as a function of W_p . The exponential dependence of α_{SOI} on W_p is related to the mode cut-off condition, i.e., the width below which the light is no longer confined in the waveguide. FEM simulations show that the cut-off width of ZEP520 coated SOIWG is 200 nm, which corresponds experimentally to ~ 60 dB/cm propagation loss in Fig. 3(b).

On the other hand, the measured propagation losses for SOIPWG are $\alpha_{SPP} = 0.2 \pm 0.08$ dB/ μ m ($W_p = 150$ nm), $\alpha_{SPP} = 0.32 \pm 0.06$ dB/ μ m ($W_p = 200$ nm), and $\alpha_{SPP} = 0.48 \pm 0.12$ dB/ μ m ($W_p = 250$ nm). The observed trend where α_{SPP} increases with W_p is rather unusual, particularly when numerical simulations normally show decreasing trend of propagation loss at increasing waveguide width. We believe

FIG. 3. (a) Loss characteristics of SOIPWG and (b) deduced propagation losses of SOIPWG and SOIWG for different widths at $\lambda = 1550\text{ nm}$. The right axis of (b) shows the propagation loss in dB/cm .

this can be attributed to material absorption of titanium adhesion layer, which is known to have large extinction coefficient in infrared wavelength range.¹⁰ Since SPP mode shifts towards the sidewalls at increasing W_p , the field overlap of SPP mode with titanium layer is also expected to increase. In addition to this, surface scattering loss will also increase due to increased interaction with gold film roughness. The total insertion loss of SOIPWG consists of (1) the coupling loss at the grating couplers (η_{grating}), (2) the coupling loss due to transition from main waveguide to narrow SOIWG (η_{SOI}), and (3) the coupling loss at SOIWG-SOIPWG interfaces (η_{SPP}).

Fig. 4 shows the coupling losses for both coated ($\eta_{\text{SOI}} + \eta_{\text{SPP}}$) and uncoated (η_{SOI}) waveguides. Here, the coupling losses have been normalized by grating coupler loss, which is measured as $\eta_{\text{grating}} \sim 4\text{ dB/facet}$. The decrease of η_{SOI} with W_p is as expected due to decreasing sidewall scattering loss resulting from the decrease of mode field size in larger W_p . The coupling loss between SOIWG and SOIPWG (η_{SPP}) can then be deduced by subtracting the total coupling loss of coated and uncoated waveguides, as denoted by dashed line.

The measured η_{SPP} increases with W_p , which increases from $\eta_{\text{SPP}} \sim 2.91\text{ dB/facet}$ ($W_p = 150\text{ nm}$) to $\eta_{\text{SPP}} \sim 13\text{ dB/facet}$ ($W_p = 250\text{ nm}$). Since SOIWG couples directly to

FIG. 4. The coupling losses of SOIWG (η_{SOI}) and SOIPWG (η_{SPP}).

SOIPWG in all our experiments (as shown by the inset of Fig. 4), we believe there is cavity effect formed by mode index differences between SOIWG and SOIPWG modes (see Fig. 2). This is well supported by our FEM simulations, where a slight change of L_p could lead to intensity buildup within SOIPWG region and results in either full-transmission (resonance) or full-reflection (anti-resonance). It is therefore possible that the coupling loss appears large when it is far from resonance condition. For this reason, the measured coupling losses for $W_p = 200\text{ nm}$ and $W_p = 250\text{ nm}$ may not be accurate as they are convoluted by such cavity effects. Furthermore, FEM simulations show the estimated coupling loss of $\sim 2\text{ dB/facet}$ for $150\text{ nm} \leq W_p \leq 250\text{ nm}$, about the same order as our experimentally measured $\eta_{\text{SPP}} = 2.91 \pm 1.57\text{ dB/facet}$ for $W_p = 150\text{ nm}$. By calculating loss due to Fresnel reflection for $W_p = 150\text{ nm}$ ($\sim 84\%$), the field overlap between SOIWG and SOIPWG can be estimated as $\sim 60\%$, in agreement with numerical simulations.

In summary, we have proposed on-chip plasmonic waveguide that can be realized through simple fabrication steps, and demonstrated propagation loss down to $\alpha_{\text{SPP}} \sim 0.2\text{ dB}/\mu\text{m}$ (equivalent to $\sim 20\mu\text{m}$ propagation length) with $\sim 2.91\text{ dB/facet}$ coupling loss. The follow up of this work would include further reduction of coupling loss that can be done by directly coupling a wider SOIWG ($W_{\text{SOI}} > W > W_p$) into SOIPWG, which is expected to give reduced Fresnel reflections and increased mode field overlap, in addition to giving suppressed cavity effect and more accurate coupling loss measurements. Different metals can always be considered for future works, particularly those of lower extinction coefficient such as silver (Ag), or those more compatible to complementary metal-oxide-semiconductor process such as copper (Cu).

The authors thank Pieter Dumon for the SOI device fabrication on ePIXnet platform. This work was supported by National Research Foundation, Singapore under NRF-G-CRP 2007-01.

¹D. K. Gramotnev and S. I. Bozhevolnyi, *Nat. Photonics* **4**, 83 (2010).

²S. K. Selvaraja, W. Boggaerts, P. Dumon, D. V. Thourhout, and R. Baets, *IEEE J. Sel. Top. Quant. Electron.* **16**, 316–324 (2010).

- ³L. Chen, J. Shakya, and M. Lipson, [Opt. Lett.](#) **31**, 2133 (2006).
- ⁴S. Zhu, T. Y. Liow, G. Q. Lo, and D. L. Kwong, [Appl. Phys. Lett.](#) **98**, 021107 (2011).
- ⁵S. Zhu, T. Y. Liow, G. Q. Lo, and D. L. Kwong, [Opt. Express](#) **19**, 8888–8902 (2011).
- ⁶Z. Han, A. Y. Elezzabi, and V. Van, [Opt. Lett.](#) **35**, 502 (2010).
- ⁷S. Sederberg, V. Van, and A. Y. Elezzabi, [Appl. Phys. Lett.](#) **96**, 121101 (2010).
- ⁸M. Dragoman and D. Dragoman, [Prog. Quant. Electron.](#) **32** (1), 1–41 (2008).
- ⁹D. F. P. Pile, D. K. Gramotnev, R. F. Oulton, and X. Zhang, [Opt. Express](#) **15**, 13669–13674 (2007).
- ¹⁰A. D. Rakic, A. B. Djuricic, J. M. Elazar, and M. L. Majewski, [Appl. Opt.](#) **37**, 5271–5283 (1998).