Experimental demonstration of CMOS-compatible long-range dielectric-loaded surface plasmon-polariton waveguides (LR-DLSPPWs)

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Abstract: We demonstrate the design, fabrication and experimental characterization of long-range dielectric-loaded surface plasmon-polariton waveguides (LR-DLSPPWs) that are compatible with complementary metal-oxide semiconductor (CMOS) technology. The demonstrated waveguide configuration represents a silicon nitride ridge atop a thin strip of metal, which is positioned on a partially oxidized layer of silicon supported by a silicon oxide layer. The demonstrated waveguides feature reasonable mode confinement (~0.5 μm²) and show rather long propagation (~700 μm) at telecom wavelengths. Owing to the existence of a metal strip within the structure, one can envision the co-propagation of electrical and photonic signals within the structure, enabling thereby seamless integration of photonic and electronic circuits. Electrical signals in metal strips supporting plasmonic modes can be used for variety of applications, e.g. to control the propagation of radiation via the thermo-optic effect.

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1. Introduction

Plasmonic waveguides are attracting growing attention in the last couple of decades owing to their unique features such as tight confinement of the electromagnetic mode to the wavelength scale and even beyond, and to the presence of metal lines within the structure, allowing the co-propagation of optical and electrical signals along the same path [1–3]. Various plasmonic waveguides and waveguide-based devices were demonstrated over the years [4–15]. A major obstacle common to all these waveguides is their limited propagation length, which is a direct result of light absorption in the metal. To diminish the absorption effect solutions such as hybrid photonic-plasmonic waveguides and long-range plasmonic waveguides were proposed and demonstrated, providing longer propagation length at the expense of weaker mode confinement [16–17].

A promising configuration ensuring decent propagation length together with wavelength scale mode confinement is the long-range dielectric-loaded surface plasmon-polariton waveguide (LR-DLSPPW) [18]. By generating a symmetric-like dielectric environment above and below a thin metal stripe, a long range mode is supported. So far, LR-DLSPPW devices were demonstrated using low index dielectric environment consisting of polymers [19]. Recently, a high index CMOS compatible LR-DLSPPW has been proposed and analyzed [20]. Alternatively, one may use other CMOS compatible materials such as titanium nitride for the purpose of plasmonic waveguiding [21].

In this work we demonstrate the design, fabrication and experimental characterization of high-index, CMOS compatible LR-DLSPPWs. Our LR-DLSPPWs are fabricated by standard microelectronic process that is compatible with standard CMOS technology and can thus be integrated with electrical functionalities and other optoelectronic components on chip. The LR-DLSPPW configuration is designed to operate in the telecom band, around 1.55 micron wavelength. Following their design and fabrication, the waveguides were characterized by near-field microscopy to reveal the modal content and by spectral transmission measurements in order to extract the transmission spectrum and propagation loss of the waveguide modes. From these measurements we have concluded that the propagation loss of the fundamental LR-DLSPPW mode is ~8 dB/mm, which is comparable to previously published results, with the estimated mode confinement being ~0.5 μm². Furthermore, as explained below, the propagation loss can be significantly reduced by improving the fabrication process of the device.
2. Design and simulations

Our LR-DLSPW (Fig. 1) consists of a Si$_3$N$_4$ ridge deposited atop a thin aluminum strip, which is supported by oxidized silicon-on-insulator (SOI) wafer. Aluminum has been selected as the metal of choice due to its compatibility with CMOS process. The dimensions of the Si$_3$N$_4$, silicon and SiO$_2$ layers were determined in order to create a symmetric-like environment, in which the LR-SPPW mode will experience minimal absorption losses [22]. Fig. 1(a) presents simplified schematics of the device configuration, while Fig. 1(b) shows the device geometry, which is the result of our fabrication process, to be discussed later in the text. Using a Finite Element Mode solver (FEM) we numerically calculated the effective propagation length ($L_{\text{eff}}$ based on the $1/e$ power criterion) of the fundamental mode as a function of several design parameters, including the thermal oxide layer thickness ($t_{\text{ox}}$), nitride rib height and width, and the misalignment of the metal strip with respect to the nitride rib. These simulations (Fig. 2) are essential for the purpose of determining the device parameters as well as for estimating the sensitivity to unavoidable imperfections that occur in the fabrication process. As a baseline, we have assumed the silicon-nitride rib height and width of 500 nm and 1 micron, respectively, aluminum strip thickness and width of 15 nm and 500 nm, respectively, and perfect alignment between the nitride rib and the metal strip. All calculations were performed based on the real device configuration, shown in Fig. 1(b).

As can be seen, the propagation length of nearly 2.5 mm is achievable with optimal parameters. Modifying the rib width and height by few tens of nm has a moderate effect on the propagation length. Interestingly, the profile of the fundamental mode varies significantly around a rib width of 0.95 um. As a result, one can observe a distinct peak in propagation length (see Fig. 2(c)) around this value. Another important observation is that a misalignment of up to 40 nm between the metal and the rib is still acceptable. In fact, the only crucial parameter is the oxide thickness. Indeed, even a slight deviation of ~20 nm in the oxide thickness results in a drastic decrease in the propagation length, towards values of ~0.3 mm. However, with modern technology, controlling the oxide thickness within accuracies much better than 20 nm is feasible and thus maintaining a long propagation length should be possible.

![Fig. 1. Schematics showing (a) the cross section of an ideal device and (b) the cross section of our fabricated device, taking into account the fabrication constrains.](image-url)
Next, we calculated the profiles and properties of 5 waveguide modes that are supported by the device at the wavelength of 1550 nm. Figure 3 shows the calculated normalized electromagnetic field distribution of these 5 modes. While all these modes can be supported, in practice the coupling efficiency to each of the modes is very different. To estimate the modal content within the device we have calculated the overlap integral of these modes with a TM polarized Gaussian beam emerging from our lensed fiber (beam waist of 2.5 microns). These results indicate that, besides the major mode [Fig. 3(b)], there is only one additional mode [Fig. 3(c)] that will be excited, albeit with a much lower coupling efficiency. According to our simulations the effective indices of these two modes are $1.78 + i \cdot 5 \cdot 10^{-5}$ and $1.5 + i \cdot 8 \cdot 10^{-4}$, respectively. Note that the fundamental mode confinement can be estimated as $\sim 0.5 \mu m^2$. 

Fig. 2. Effective propagation length as a function of (a) thermal oxide layer thickness, nitride rib (b) height and (c) width, and (d) aluminum strip misalignment from the center of the nitride rib.
Fig. 3. (a) Schematic cross section of the as-fabricated device. (b,c,d,e,f) Electromagnetic field norm distributions of the modes supported by our LR-DLSPPW. In practice, TM polarized light from an external fiber couples only to the modes shown in panels (b,c).

3. Fabrication

The fabrication process is depicted in Fig. 4. Our substrate is silicon-on-insulator (SOI, SOITEC) consisting of a 340-nm-thick crystalline silicon layer on top of a 2-μm-thick buried oxide. Firstly, a 310-nm-thick silicon oxide layer (SiO₂) was thermally grown by partially oxidizing the silicon layer. As a result, the silicon layered was thinned down to about 190 nm. Next, the metal strip was patterned using a standard lift-off procedure starting with electron-beam lithography (EBL) followed by evaporation of a 15-nm-thick aluminum film and completed with the removal of the inverse resist along with the metal covering it. Next, a 500-nm-thick silicon nitride layer (SiN) was deposited by plasma enhanced chemical vapor deposition (PECVD) at 300°C and a metal mask defining the optical structure consisting of the hybrid plasmonic waveguide, the input/output photonic waveguides and a 100μm long tapered couplers was patterned using standard lift-off procedure with 120 nm thick aluminum. Finally, we used three different reactive ion etching (RIE) processes to etch the SiN, SiO₂ and Si layers.
Fig. 4. Schematic description of the device fabrication flow: (a) planar substrate, (b) oxidation of the SOI, (c) aluminum liftoff, (d) nitride deposition, (e) aluminum liftoff, (f) reactive ion etching (RIE).

A scanning-electron microscope (SEM) image showing a typical cross section of the LR-DLSPPW prior to the metal mask removal is presented in Fig. 5.
3. Experimental results

To characterize the propagation loss of the device we have fabricated several devices with different lengths, and launched a TM (out of plane) polarized light generated by a diode laser operating in the 1.54-1.56μm wavelength regime. The light was launched into the waveguides using a polarization maintaining lensed fiber with a mode size of 2.5μm. Similarly, light was collected from the output facet of the waveguide by another tapered fiber and detected by an InGaAs photodetector (HP 81634A). To remove the effect of Fabry-Perot oscillations, each measurement was performed by scanning the above mentioned wavelength range and extracting the mean value of transmission. Furthermore, in order to differentiate between inherent absorption losses (occurred in the metal strip) and additional losses that originate from absorption and scattering by the silicon nitride rib and were neglected in the simulation, we have repeated the same measurement using a reference sample consisting of a similar structure, albeit without the metal layer. The measured transmission results for the two sets of samples are presented in Fig. 6.

![Fig. 5. SEM image showing a cross section of the LR-DLSPPW device. The various material layers are highlighted.](image)

Before discussing the loss of the actual plasmonic device, we should consider the loss of the reference sample, i.e., without metal, shown in Fig. 6(b). By performing a linear fit to the
measured data, we found the propagation loss of this structure to be ~2 dB/mm. The reason for the relatively high loss becomes clear by observing the rib surface (Fig. 7), in which noticeable surface roughness is evident. We measured the amplitude of the surface roughness to be in the range of 20-40 nm. Indeed, a propagation loss of ~2db/mm is an acceptable number for such values of roughness, as calculated e.g. by Payne and Lacey [23].

![Fig. 7. SEM image of the side walls of the LR-DLSPPW](image)

After establishing the origin of propagation loss in the reference sample, we can now analyze the propagation loss in the plasmonic sample. For a given waveguide length 2L, each sample consists of a hybrid plasmonic waveguide of length L which is butt coupled to a reference waveguide of length L. Thus, we first subtract the loss (2 dB/mm) of the reference waveguide. The remaining loss is that of the plasmonic waveguide. This obtained loss is presented in Fig. 6(a) as a function of the waveguide length L. By performing a linear fit to the obtained data the propagation loss of the hybrid plasmonic waveguide was found to be ~6db/mm. Keeping in mind that ~2dB/mm loss is originated from the surface roughness of the dielectric structure, we conclude that the loss originated from the radiation damping in the metal is in the order of 4dB/mm, i.e. corresponding to a propagation length of about 0.7 mm. Comparing to our computer simulations (Fig. 2), such a value of propagation length can be explained, e.g. by a ~50 nm misalignment of the Al strip with respect to the nitride ridge. Other reasons can be related to roughness in the Al strip, slight deviation in the thickness of the oxide layer, or combination of all the above. In order to improve the propagation length of the waveguide the surface roughness should be reduced by optimizing the etching process via controlling the RF power and the gas mixture. The roughness can also be reduced by smoothing the metal mask.

Finally, in order to confirm that our waveguide supports two modes, we performed near-field scanning optical microscopy measurement (NSOM, Nanonics MultiView 4000), in which our metal coated NSOM probe, with aperture of 250 nm, scanned the top of the hybrid plasmonic waveguide. Figure 8(a) presents a near field optical intensity distribution on top of the silicon nitride (256x256 pixels). The obtained result show a clear trace of modal beating, as evident by the periodic structure along the propagation direction. For comparison we plot the simulated mode propagation of the two modes. The periodicity was measured to be ~5.5
microns, corresponding to a difference of 0.28 in the effective index of the two modes. This is in excellent agreement with the predicted effective index values of 1.78 and 1.5. Figure 8(c) shows the measured and the simulated cross sections of the near field at the center of the waveguide. Again, the measured result is in excellent agreement to the simulation.

![Figure 8](image.png)

As previously mentioned, the loss of the two modes is very different. According to our simulations the first mode has an effective index of \(1.78 + i \cdot 5 \cdot 10^{-5}\) and the second has an effective index of \(1.5 + i \cdot 8 \cdot 10^{-4}\). As a result, the contrast of the beating decays as the modes propagate along the waveguide.

5. Conclusions

In summary, we designed, simulated and experimentally demonstrated the fabrication and the measurements of CMOS compatible LR-DLSPPWs. We characterized the propagation length of the device and found it to be \(\sim 0.7\) mm. Owing to its promising characteristics of easy contact reach and good propagation length, the LR-DLSPPW can potentially become an important building block in future on-chip optoelectronic circuitry.

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