Silicon-plasmonic internal-photoemission detectors for 40 Gbit/s data reception: supplementary material

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This document provides supplementary information to “Silicon-plasmonic internal-photoemission detectors for 40 Gbit/s data reception,” <http://dx.doi.org/10.1364/optica.3.000741>. It contains a discussion of the detector absorption characteristics and a detailed description of the PIPED fabrication. Further details are given for the opto-electronic characterization of the detectors and passive photonic components. © 2016 Optical Society of America

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1. Power Attenuation Constant and Device Length

The power attenuation constant α in the photodetector core determines the lower limit for the minimum technically useful device length. We use a two-dimensional finite-element method to numerically compute the complex-valued effective refractive index $\underline{n}_{\text{eff}} = n_r - jn_i$ associated to the eigenmodes ψ of the MSM waveguide with dominant horizontal and dominant vertical field orientation. We use experimentally obtained data for the complex frequency dependent permittivities of Au [1] and Ti [2]. The imaginary part of the effective refractive index n_i and the free-space wavenumber $k_0 = 2\pi/\lambda$ define the power attenuation constant $\alpha = 2k_0n_i$. The associated absorption length for which the optical intensity has decayed by a factor of $1/e$ is given by $l_{\text{abs}} = 1/\alpha = 1/(2k_0n_i)$. Figure S1 shows the absorption lengths for the eigenmodes of the detector core with dominant vertical or horizontal field alignment as a function of the detector core width w . The absorption length is significantly smaller than $1\ \mu\text{m}$ for $w < 150\ \text{nm}$ for either field orientation. This is due to an ever increasing field confinement inside the detector core as the junction width w is decreased. A large field overlap with the absorbing Ti layer leads to a rapid absorption of light. The absorption length increases again for the dominant vertical field orientation at widths $w < 100\ \text{nm}$ as the mode is increasingly

Fig. S1. Absorption length in the detector core as a function of the core width for the eigenmodes with dominant horizontal and vertical field orientation. The insets exemplarily show the associated optical field magnitudes at a silicon core width of $w = 150\ \text{nm}$.

guided outside the MSM junction, farther away from the Ti. Taking five absorption lengths as a basis, detectors with a length between $(2.5 \dots 5)\ \mu\text{m}$ absorb more than 99 % of the optical field, depending on the detector width and the polarization. These short absorption lengths enable ultra-compact plasmonic photodetectors.

Fig. S2. Fabrication sequence of plasmonic internal-photoemission detectors (PIPED) (a) 80 nm thick thermal oxide is grown and patterned on top of a weakly p-doped silicon on insulator (SOI) wafer with a device layer height of 340 nm in x-direction. The Si height after oxidation is 300 nm. (b) The hard mask is undercut using isotropic etching of silicon with an SF_6 chemistry at room temperature. The hard mask is unaffected due to the high selectivity of SiO_2 over Si. The ratio of vertical to lateral etch rate is ~ 3 . The Si core remains mechanically stable for the width $w = 75$ nm. (c) Au or Ti are deposited on the sidewall of the Si core under grazing incidence. The hard mask serves as an evaporation shadow preventing electrical shortcut. (d) SEM image of the undercut hard mask before metallization. The hard mask is translucent and reveals the underlying Si core. The inset shows a magnified image of the silicon core with a width of $w = 75$ nm. The Si tapers connect the plasmonic section to photon waveguides on either side of the detector. The photonic parts are protected from metallization by a PMMA resist layer.

2. Fabrication

The fabrication of ultra-narrow MSM waveguide structures with semiconductor layer thicknesses below 100 nm, smooth sidewalls and different metal layers without direct contact poses a considerable challenge on nanofabrication. While direct etching of metal-coated waveguides via a reactive-ion etching (RIE) or reactive ion beam etching (RIBE) process suffers from poor selectivity of resist over metal, multiple lift-off processes become very critical in the sub-100 nm range. Therefore, we introduce a new process that is based on direct metal evaporation at self-masking silicon nanowires.

Here, the process is demonstrated for silicon-on-insulator (SOI) chips with a low p-doped 340 nm silicon device layer (resistivity $\sim 10 \Omega\text{cm}$). The SOI chips are first thermally oxidized to create an 80 nm thick top oxide layer. The oxide layer is patterned using electron beam lithography and RIE with a CHF_3 chemistry, generating a hard mask for the layout of photonic and plasmonic sections on the residual 300 nm silicon device layer (Fig. S2 (a)). Subsequent electron beam lithography with PMMA resist opens the plasmonic sections and defines the contour of the electrodes for external electronics. The resist layer serves as a mask for an isotropic etching step with SF_6 at room temperature (Fig. S2 (b)). The SF_6 only attacks the silicon in the opened plasmonic and electrode sections and leaves the oxide unharmed. The oxide hard mask is undercut and the electrode areas are etched down to the buried oxide. As a result, a silicon nanowire with an oxide cap is created. Due to the isotropic nature of this etching step, the surface

roughness of the silicon is well below the roughness of the original mask of below 20 nm. The structure is mechanically stable for lateral nanowire widths of $w = 75$ nm and below. In a further step, the undercut oxide serves as a hard mask for metal evaporation at grazing incidence with respect to the plane of the chip from both sides of the nanowire using different metals (Fig. S2 (c)). Under such condition, an asymmetric MSM junction is created without an electrical short circuit. The metal thickness of approximately 40 nm was chosen to exceed the SPPs penetration depth. With a carefully designed PMMA mask for angled metallization there is no fundamental limit in the device length, and devices with a length $L < 5 \mu\text{m}$ become possible. This processing is not restricted to metals. In principle, any desired lateral layer sequence can be achieved, given that the materials can be directionally deposited. After metal lift-off, the remaining silicon is fully etched with an anisotropic SF_6 etching step at cryogenic temperatures. The previously patterned oxide hard mask is used to transfer the photonic waveguides and the diffraction grating couplers into the silicon device layer. The photonic waveguides have a width of 400 nm and a Si height of 300 nm. The 80 nm thick oxide hard mask is not removed. Fig. S2 (d) shows an SEM image of a plasmonic section before metallization. The plasmonic sections are connected to Si photonic waveguides by Metal-Si-Metal tapers. This processing scheme allows for fabrication of lambda-scale active plasmonic devices with electrode distances below 75 nm.

3. Opto-Electronic Characterization

Light at the wavelength of 1550 nm is amplified in an Er-doped fiber amplifier (EDFA) and coupled into the fabricated chip by diffraction grating couplers. The photonic waveguide mode is excited with a dominantly horizontal electric field component. The coupling losses of the grating couplers and the propagation losses of the photonic waveguides are assessed with the subtraction method. The transmission T of photonic reference waveguides is determined as a function of waveguide length l , see Fig. S3. The transmission as a function of waveguide length is a linear function on a semi-logarithmic scale. The slope m of this function is the waveguide propagation loss amounting to $m = 2$ dB/mm. The y-intercept T_0 corresponds to two times of the grating insertion loss, $T_0/2 = 10.1$ dB. The high propagation losses of the SOI waveguides are due to the surface roughness of the non-optimum negative-tone resist that was used to structure the SiO_2 hard mask. This loss contribution can be reduced to the order of 1 dB/cm using high-resolution resists like HSQ [3].

We use an RF probe with ground signal (GS) electrode configuration to pick up dark current I_d and photocurrent I_p from the device. The photodetector is biased with a precision source/measure unit (Agilent B2960A). For DC measurements, the

Fig. S3. Determination of photonic waveguide propagation loss and grating coupler insertion loss.

current-voltage characteristic is measured under illumination at various power levels P . Measurements at dark conditions serve as a reference to assess the photocurrent $I_p = I - I_d$ and the sensitivity $S = I_p / P$.

For Polarization sensitive measurements, we cleave SOI chips and accessed the photonic waveguides from the chip edges using polarization maintaining (PM) fibers. The slow polarization axis of the fiber is aligned with the surface normal of the photonic chip. For alignment of the coupling fiber, we use a rotatable fiber holder and a free-space polarizer. The orientation of the linear polarization at the input of the PM coupling fiber is then controlled with a fiber-coupled half-wave plate (Thorlabs PC FFB 1550). The half-wave plate allows rotating the polarization corresponding to a full 360° revolution of the electric field vector at the input of the PM fiber. Due to the strong birefringence of the PM fiber, only input electric fields parallel to one of the polarization axes represent a linear polarization at the input of the photodetector.

For opto-electronic bandwidth measurements, a bias tee is inserted into the electronic circuitry after the probe to split electronic DC and RF signals. A 2-port vector network analyzer (VNA, Anritsu 37397C) is used to drive a Mach-Zehnder Modulator (MZM), creating an intensity modulated signal. The optical signal is received by the PIPED and the electrical signal is returned to the VNA. The RF-network is referenced with a photodetector standard (Anritsu MN4765A). The RF-probe is not referenced for.

4. Data Reception Experiment

Infrared light at the wavelength of 1550 nm is launched into a MZM. The intensity of the optical signal is encoded with a pseudo-random bit sequence (PRBS) with a bandwidth of up to 40 Gbit/s, resulting in an on-off keying optical signal. This is the highest data rate directly available in our labs. The modulated light is amplified by an EDFA, then coupled to the Si chip and received by the biased PIPED. The electric signal is directly amplified after the RF-probe and a sampling head of a digital communication analyzer records the eye diagram (Agilent 86100 Infiniium DCA-J C).

References

1. R. L. Olmon, B. Slovick, T. W. Johnson, D. Shelton, S.-H. Oh, G. D. Boreman, and M. B. Raschke, "Optical dielectric function of gold," *Phys. Rev. B* **86**, 235147 (2012).
2. M. A. Ordal, R. J. Bell, R. W. Alexander, L. A. Newquist, and M. R. Querry, "Optical properties of Al, Fe, Ti, Ta, W, and Mo at submillimeter wavelengths," *Appl. Opt.* **27**, 1203-1209 (1988).
3. D. K. T. Ng, W. Qian, L. Kim-Peng, P. Jing, T. Kun, L. Yicheng, L. Chee-Wei, and H. Seng-Tiong, "Effects of SiO₂ hard masks on si nanophotonic waveguide loss for photonic device integration," *IEEE Photon. Technol. Lett.* **26**, 70-73 (2014).