Supporting Information

Highly Efficient Excitation of Surface Plasmons Using a Si Gable Tip

[1]Arnab Dewanjee , [1,2]M. Z. Alam, [1] J. Stewart Aitchison [1]Mo. Mojahedi

[1]Department of Electrical and Computer Engineering,

University of Toronto, 40 King's College road, Ontario-M5S3G4, Canada

Now: [2]California Institute of Technology, Pasadena, California, USA

Author email: arnab.dewanjee@mail.utoronto.ca

Fabrication method:

Figure S1 shows the steps for fabricating the gabled Si tip SPP excitation device. To fabricate the sample, we first obtained a <100> Si wafer and grew 300 nm of SiO_2 by thermal oxidation (18 mins in the Bruce technologies oxidation furnace at the Toronto Nano-fabrication Center-TNFC). Then we cleaved a small piece of sample from the oxidized Si wafer. As the next step, we made patterns of 500 nm wide lines and 200 μm square pads of ma-N 2400 negative resist on top of the oxidized Si sample using Vistec E-beam lithography unit. Next, we etched the oxide layer using deep reactive ion etching using an Oxford Instruments PlasmaPro Estrelas100 DRIE System unit at the TNFC facilities. After that, we wet-etched the oxide masked Si sample in 45% KOH solution for 7 mins at 80^0 C temperature to create the gabled Si tip structures. The height of the gable tip after the wet etch was measured to be 6 μm. Next, we deposited a thick (more than 6 μm) PECVD oxide on top of the Sample containing the Si tip, using an Oxford Instruments PlasmaLab System 100 PECVD unit. Then we planarized the top surface of the deposited PECVD oxide using chemical mechanical polishing (CMP). The CMP of the top surface was carried out until the top oxide thickness was reduced to the approximate height of the tip of the Si chimney tip. Further CMP was not carried out to avoid destruction of the Si tip. We also polished the bottom surface of the sample (rough Si) for reducing the defused reflection while coupling light from the bottom. As the next step, we patterned negative resist (ma-N 2400) on the oxide surface for metal deposition and grating fabrication by lift off using the same electron beam lithographic system at TNFC. We used the 200 μm square Si marker pads for alignment of the resist patterns for proper positioning of the grating. Then we deposited gold on top of the patterned resist using a Datacomp Electronics TES12D Thermal Evaporator and carried out lift off to fabricate the grating. In the sample layout, hence in the fabricated sample as well the 1st grating was 10 microns away from the tip of the Si chimney. We fabricated several other gratings at varying distances from the Si tip to monitor the decay of the excited surface plasmon polariton as mentioned in the manuscript. Figure S2 shows the layout of the fabricated sample with the little opening for visualization of the tips under the metal (vis. gap) during measurement and the gratings at different distances from the tip.

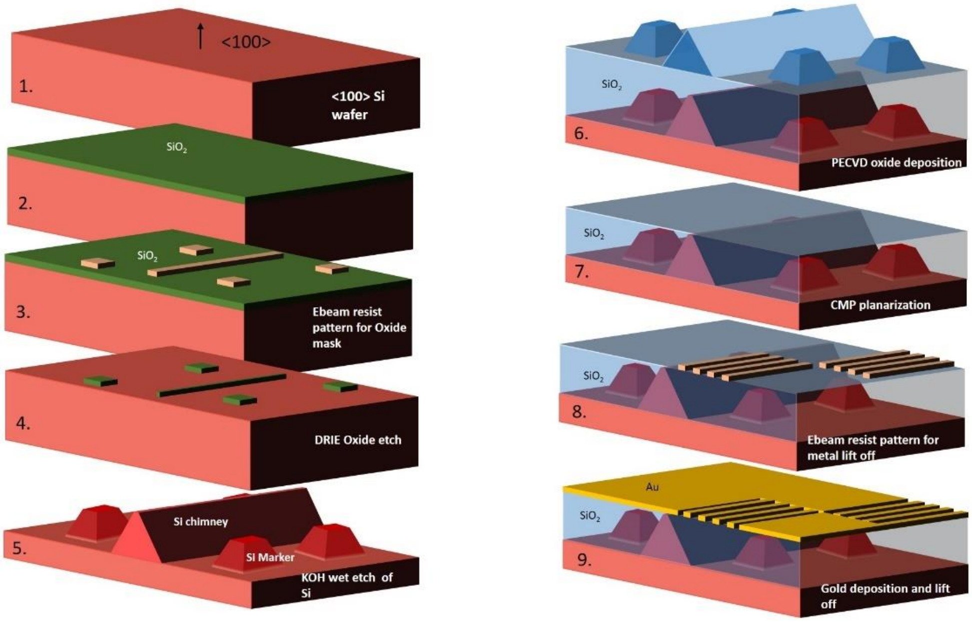

Figure: S1. Steps of fabricating the on chip Si gabled tip SPP excitation device. The steps are numbered according to the order they were carried out during the fabrication process.

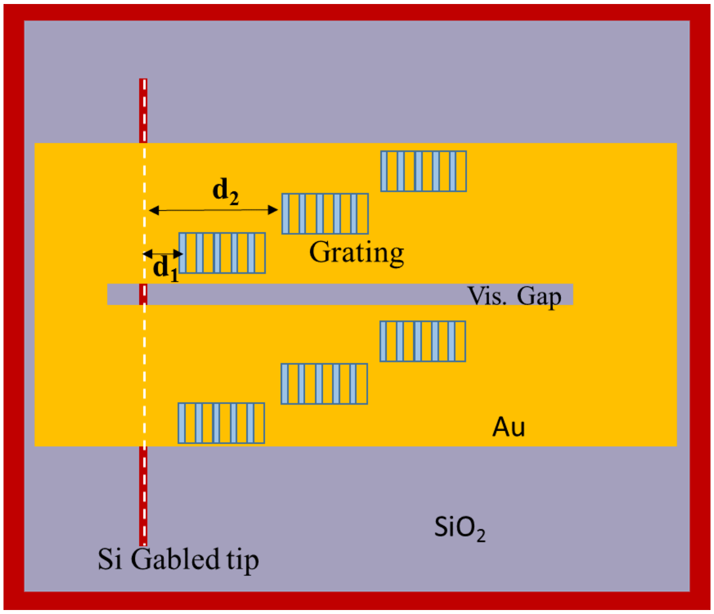

Figure: S2. Top view of the floor layout plane for the sample fabrication

Measurement Setup

We used two different setups for the measurement of the efficiency of the SPP excitation and the measurement of the radiation pattern from the gratings as mentioned in the manuscript. For efficiency measurement, we used the setup as shown in figure S3(a). Light was collected from a JDS Uniphase SWS15101 Tunable Laser Source tuned to the 1550 nm center wavelength, using a single mode fiber (SMF). The output light of the SMF was converted to a free space Gaussian beam using a fiber collimator lens. The free space Gaussian beam then propagates through a polarization control optics section in the setup, then collected and coupled to the base of the gabled Si tip using Newport F-L40B objective lens. The Si tip excites the SPP mode at the Au/SiO_2 interface which then propagates and then gets coupled out to the radiation mode from the grating. At the output from the grating, light was collected using a Newport M40X objective lens and focused onto the Newport 818-IR detector for power measurements or a Xenics XEVA-1324 IR camera for imaging purpose.

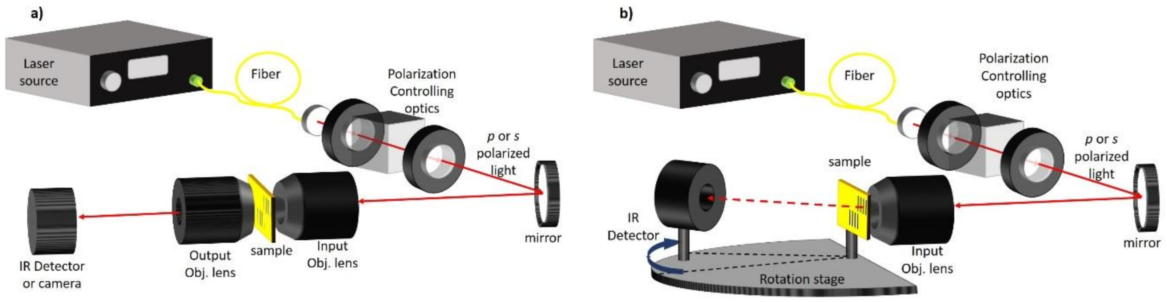

Figure: S3. a) A Schematic of the experimental setup for imaging the radiated surface plasmon from the metallic grating. b) A schematic of the experimental setup for measuring the radiation pattern of the metallic grating with a movable detector.

For measurement of the radiation pattern, the setup is depicted in figure S3(b) in which the beam traverses through the similar components as shown in figure S3(a) and delivered to the base of the Si tip. In this case, the sample was attached to the fixed center stage of the home-built radiation pattern measurement setup. A Newport 818-IR detector was attached to a rotational stage which revolves around the sample to collect scattered light from the grating and measure the radiation pattern of the sample on the center stage.

SPP excitation Efficiency calculation from measured data:

As mentioned in the manuscript, we extrapolated the unidirectional SPP excitation efficiency of the fabricated sample for a 10 μm wide input beam at 1550 nm, from the measured data. For the purpose we calculated the normalized power decay of the SPP mode excited by the Si tip (in simulation) and also measured the power radiated from the gratings fabricated at different distance (6 μm, 66 μm and 96 μm)) from the SPP excitation point of d_{SPP} = 4 μm (see figure 3(a) of manuscript).

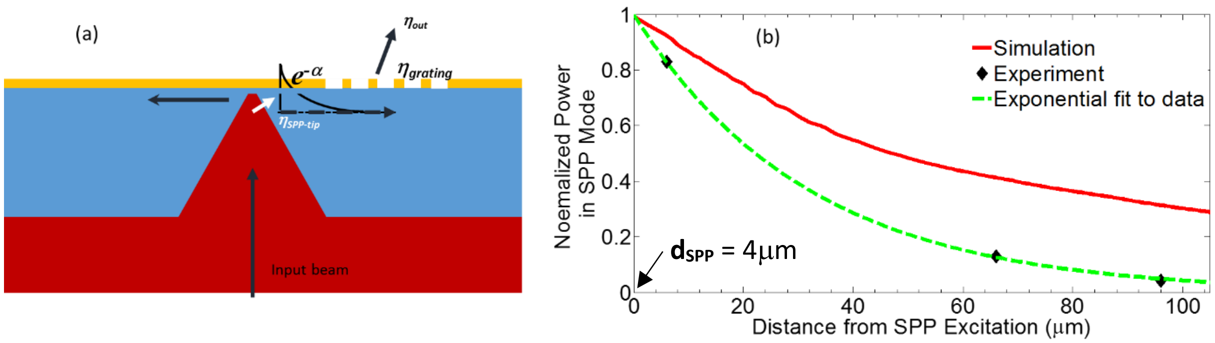

Figure: S4. (a) Schematic of the end view of the Si tip SPP excitation scheme. (b) Normalized power decay of the SPP mode excited by the Gabled Si tip. The red solid curve plots the decay profile of the Au/SiO_2 single interface SPP mode excited by the Si tip, the diamond shaped data points are measured normalized power radiated from the gratings at different distances and the greed dashed curve is the exponential fit to the measured data points

Due to the effects of fabrication imperfections (i.e. roughness at the Au/SiO_2 interface, random scattering centers, lower grating conversion efficiencies in reality) the attenuation of the propagating SPP mode in the device is larger than the attenuation of the SPP mode at the calculated smooth Au/SiO_2 interface. As mentioned in the manuscript, 8.89% (η_{out}) of the light from the input beam is radiated out from the grating at the preferential angle designed to out-couple the SPP. A quick simulation plugging the fabricated grating parameters obtained by scanning electron microscopy, gives us a 42% grating conversion efficiency ($\eta_{grating}$ as shown in figure S4(a)). The Red solid curve in figure S4(b) plots the calculated decay profile of the normalized power in the SPP mode excited by a gabled Si tip. The black diamond shaped data points are the measured normalized power radiated from the gratings at different distances from the tip position as shown in figure 3(a) of the manuscript (the reader may also refer to figure S2). The horizontal axis in figure S4(b) displays the distance from the SPP excitation point (**d_{SPP}** = 4 μm) along the Au/SiO_2 interface in the direction of propagation hence, representing the actual distance propagated by the excited SPP. The green dashed curve in figure S4(b) is an exponential fit to the black diamond shaped data points obtained from measurement. The parameter α (figure S4(a)) accounts for the attenuation (due to propagation) of the SPP mode excited by the Si tip (see figure S4(a)). The calculated value of α associated to the red solid curve in figure S4(b) is 0.0127/μm (α_{calc}). The value of α associated to the green dashed curve (exponentially fitted to the data points of measurement) is 0.0312/μm ($\alpha_{exp-fit}$). Such significant difference in magnitudes of α_{calc} and $\alpha_{exp-fit}$ is a clear indication of the fact that the imperfect fabrication resulted in a higher attenuation (due to propagation) of the excited SPP in the fabricated sample. The extrapolation of the actual SPP coupling efficiency ($\eta_{SPP-tip}$) is done using the following equation:

$$\eta_{SPP-tip} = \frac{\eta_{out}}{\eta_{grating}} * e^{\alpha_{exp-fit}*L} \qquad (1)$$

The obtained efficiency ($\eta_{SPP\text{-}tip}$) for a propagation distance of L = 6 μm in equation 1 was 25.52%. The differences in the values of α_{calc} and $\alpha_{exp\text{-}fit}$ comes from the fact that α_{calc} was calculated considering a perfectly smooth Au/SiO_2 interface and a perfect homogeneous SiO_2 layer underneath the Au layer. In reality, the Au/SiO_2 interface in the fabricated sample was not perfectly smooth; also, random scattering centers could exist in the SiO_2 layer near the interface. Therefore, as expected, $\alpha_{exp\text{-}fit}$ was found to be larger than the α_{calc}.

SPP excitation Efficiency calculation approach in simulations:

We used the commercial grade FDTD simulator from the Lumerical Inc. for all our simulations. The term ‘SPP excitation efficiency’ has been used repeatedly in the manuscript. We have used the ‘mode expansion monitor’ of the Lumerical FDTD software to calculate this SPP excitation efficiency. For a better understanding, we advise the reader to refer to the document provided by Lumerical Inc. in their online documentation (Lumerical Knowledge base mode expansion monitor).