E-beam-lithography free plasmonic slot waveguides for on-chip Raman spectroscopy

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We present nanoplasmonic slot-waveguides interfaced to dielectric photonic waveguides and capable of strongly enhancing Raman scattering. Their e-beam-free fabrication can be scaled to volume manufacturing and makes the plasmonic structure, hence the Raman spectra, reproducible.

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Nanoplasmonic structures can strongly enhance Raman scattering, an effect being exploited in surface enhanced Raman spectroscopy (SERS) [1]. Over the past decade, the development of SERS substrates has focused on making the plasmonic enhancement stronger and more reproducible. Among many technological approaches, substrates with nano-patterned plasmonic antennas have been demonstrated with good performance. Parallel to that effort, Raman sensors based on waveguide enhancement have been developed with the goal of integrating a full Raman spectroscopy system on a low-cost CMOS-compatible chip [2-4]. Here we report a nanoplasmonic waveguide patterned on a SiN slot waveguide capable of strong and reproducible SERS enhancement. By using atomic layer deposition (ALD) and subsequent gold sputtering, we manage to fabricate <50 nm gaps using a scalable fabrication method.

This plasmonic waveguide is a gold metal slot waveguide, where a narrow slot width (g) results in a strong field intensity in the gap. Given the targeted operating wavelength of 800 nm, a suitable slot width is of the order of 10 to 50 nm for a waveguide being 300 nm thick. As this dimension is currently incompatible with deep-UV lithography, we narrow down the slot using ALD as shown in figure 1.c. We start from a deep-UV (193 nm) patterned SiN slot waveguide, followed by a conformal coating of 50nm of Al_2O_3 via atomic layer deposition [5] performed thermally at a pressure of 10^{-6} mbar. Finally, a 100 μm long portion of the waveguide is coated by 70 nm of gold via sputtering. The gap of the final hybrid plasmonic structure is therefore well controlled and set to 40 nm.

Fig1. (a) The schematic of the device, (b) Normalized $|E|$ of hybrid plasmonic-photonic mode, (c) The process flow and (d) SEM images of fabricated device.

Fig2. (a) The background subtracted Raman spectrum of NTP (blue-dotted line) and of an un-functionalized Al_2O_3 coated SiN waveguide (orange – bold line) (b) The mean standard deviation % for all NTP modes evaluated over 24 waveguides on three different chips. The red dotted line shows the average MSD over all the Raman modes (c) the 1572.9 cm^{-1} mode of NTP measured on three different chips.

Three different chips each containing 8 plasmonic hybrid waveguides and a reference dielectric waveguide were fabricated. Each plasmonic waveguide is preceded by a dielectric one so that light is coupled from free space to the TE mode of that dielectric (access) waveguide and then to the hybrid slot waveguide. The length of the dielectric portion varies from waveguide to waveguide but is always greater than 100 μm . To characterize our device, we coat it with a gold-binding monolayer of 4-nitrothiophenol (NTP). We recorded the Raman spectra in a back-reflection geometry, as shown in figure 1.a, using a confocal Raman microscope (Witec Alpha 300 R+, equipped with 100x/0.9 objective, 785 nm laser and -70°C-cooled Andor IDUS 401 CCD camera) using a power of 1 mW (before objective) and 1 s integration time, as described in [6].

Fig 2.a shows the Raman spectrum of NTP measured from the plasmonic waveguide and compared to the Raman signal collected from a reference waveguide. The large field enhancement allows to distinguish clearly all the vibrational modes of NTP. A signal-to-background noise ratio of around 103 was observed for the 1339.8 cm^{-1} vibration, a value superior to earlier waveguide-based SERS demonstrations [6, 7]. To demonstrate the robustness of the fabrication, we have measured the Raman spectrum from 24 waveguides from 3 different chips and calculated the mean standard deviation (MSD) of all the NTP Raman modes. The result in figure 2.b shows an average MSD of 5.7 %. The increased variability at the 1080.9 and 1339.8 cm^{-1} modes can probably be attributed to chemical instability of the NTP exposed to high optical fields [8]. In figure 2.c the Raman peak at 1572.9 cm^{-1} shows a high peak-to-background reproducibility over all the three chips while the increase in background is only due to longer dielectric access waveguide.

The absolute enhancement in terms of Raman conversion efficiency (η_s) that is calculated from the NTP 1340 cm^{-1} peak is $9.3 \times 10^9 \text{ sr. cm}^{-1}$. This is almost 5 orders of magnitude better than the reported value of η_s for SiN slotted waveguides [9]. The hybrid photonics-plasmonics waveguide also compares favorably with bowtie antennas that were previously demonstrated to interface well with photonics circuits but suffered from low and narrowband enhancement, larger background noise and the need for e-beam lithography [7]. Moreover, our SERS waveguide shows a very good reproducibility that is often problematic for SERS substrates.

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Abstract

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