Nanojet and Surface Enhanced Raman Spectroscopy (NASERS) for Highly Reproducible and Controllable Single Molecule Detection

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ABSTRACT

The nanojet and surface enhanced Raman spectroscopy (NASERS) has been demonstrated in this paper. It consists of two enhancement mechanisms: optical confinement of nanojet to deliver enhanced power in a small volume and plasmonic resonance due to nanostructured metal surface. The enhancement of Raman signal was experimentally demonstrated to be 183 times larger than traditional SERS effect obtained from the same substrate. Non-resonance Raman scattering of ultralow concentration (10^{-12} M) R6G has also been performed to show the potential of NASERS to be a simple and reliable technique for single molecule detection application.

INTRODUCTION

In order to improve the sensitivity in chemical analysis and biological detection, researchers have continued to lower the detection limit to the level of single molecule. It was firstly achieved by fluorescence microscopic method. [1-3] However, fluorescence signal provides limited information and positive identification of targeted molecule was not possible. In contrast, vibrational spectroscopy such as Raman spectroscopy provides the capability to detect and precise identify the- molecule from their vibrational modes. [4] In general, typical scattering cross section of Raman signal ranges from 10^{-25} to 10^{-30} cm^{-1}, which hinders this technique to successfully identify molecules at low concentration. Surface enhanced Raman spectroscopy (SERS) has overcome this limitation and significantly increases the effective scattering cross section to the same order of other spectroscopic methods such as fluorescence spectroscopy. [5] It is achieved by locating the targeted molecule to the proximity of roughened metal surface or metal nanoparticles. [6] The enhancement is contributed by two mechanisms. One is the charge transfer enhancement, which is due to the additional electronic transition between metal and targeted molecule. [7] The other mechanism is electromagnetic enhancement. The targeted molecule experiences higher electric field by the localized surface plasmonic resonance (LSPR) of noble metal material. As a result, the Raman signal can be substantially amplified by approximately the ratio between localized and incident field to the fourth power. [8]

First observation of single molecule Raman spectroscopy was achieved by mixing targeted molecule into metal nanoparticle colloidal solution. The “hotspots” from the aggregation of nanoparticles contributed remarkably strong coupling effect for detecting few or even single targeted molecule. [9] Nevertheless, the aggregation of nanoparticle colloidal is difficult to control. As a result, neither the SERS performance nor the hot spot location is predictable, which is undesired for repeatable and reliable sensing applications. Later on researchers utilized another method to fabricate bottom-up nanostructured SERS substrate with the advancement of nanofabrication technique. So far, different approaches have been adopted such as e-beam lithography, focus ion beam milling, nanosphere template deposition to fabricate bottom-up

SERS substrate. [10-12] However, a reliable and simple fabrication method for fabricating low cost and single molecule level SERS substrate is still a challenge.

In 2004, Chen et al. proposed a simple but effective way to perform subwavelength two-dimensional confinement of plane wave by micro-scale infinite dielectric cylinder. [13] The simulation results demonstrated that a "photonic nanojet" can be induced at the shadow side of microcylinder. In consequence, the back scattering of nanoparticle located near the nanojet can be enhanced by 3 to 4 orders. Subsequently, it was proposed that a three-dimensional subwavelength confinement of optical field can be achieved in photonic nanojet system by applying incident Gaussian beam instead of plane wave incident light. [14] Based on this phenomenon, nanojet enhanced Raman scattering has been demonstrated on planar geometries with the enhancement of two orders of magnitude. [15]

Here we proposed to combine the two enhancement approaches, i.e. plasmonic and nanojet enhanced methods on non-planar SERS structures, in order to construct a stable platform for single molecule label-free detection. Previously our group has demonstrated a cost-effective, simple and reliable fabrication technique applicable for wafer-scale and ultrahigh sensitivity nanostructured SERS substrate by thermal dewetting technique. [16] The enhancement factor has been reported up to 10^8. Upon the enhancement achieved from plasmonic nanostructred SERS substrate, the dielectric microsphere additionally confines the incident field and is expected to boost the enhancement significantly. This microsphere-analyte-nanostructured SERS substrate configuration will provide a simple and effective method to enhance the Raman signal. Moreover, the three-dimensional confinement from nanojet effect offers additional advantage of reducing detection volume.

EXPERIMENT

NASERS Device Fabrication

The schematic of NASERS device preparation is shown in figure 1 (a). The substrate used was p-type doped silicon wafer with crystalline orientation of <1,0,0>. A 6 nm Au thin film was deposited on the substrate by e-beam evaporation. Then thermal dewetting technique was performed to generate self-assembled Au nanoparticles (AuNPs) pattern. The annealing was conducted for 90 s at 500 °C. After obtaining AuNPs, the pattern was transferred onto substrate by reactive ion etching technique. Finally another thicker layer of 50 nm Ag was deposited on nanostructured substrate. This process can significantly increase the hot spot effect by reducing the gap among metal nanostructures

After nanostructured SERS substrate has been fabricated, a 5 µL droplet of targeted molecules was placed onto the SERS substrate. Once the targeted molecule solution was completely dried, a 2 µL of 5 µm SiO_2 microsphere solution was hand-dropped onto the sensing region to form the sandwich configuration of microsphere-analyte-nanostructured SERS substrate. Figure 1 (b) shows the scanning electron microscopy (SEM) images of nanostructured SERS substrate. It can be observed that the Ag is mainly deposited on the top of the silicon nanostructures and forms a highly compacted Ag nanoparticle array. It helps to create a high density of hot spot coupling effect for SERS enhancement.

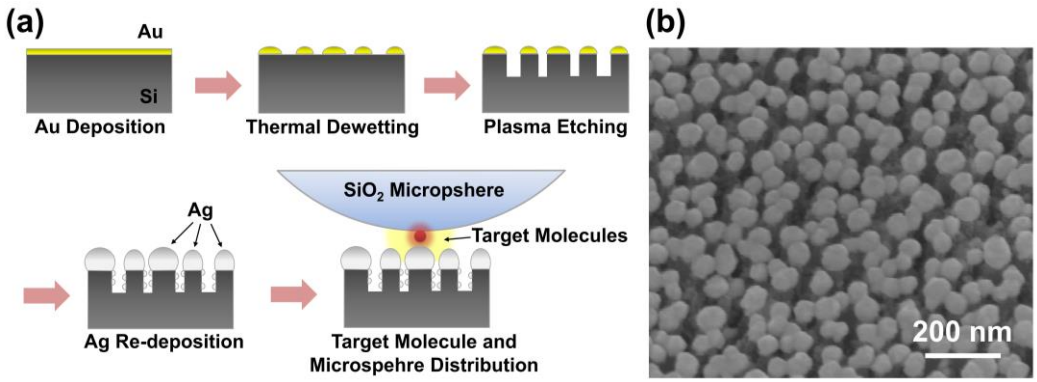

Figure 1. (a) Schematic of the NASERS setup preparation; (b) 30 degree tilted SEM images of nanostructured SERS substrate.

FDTD simulation

The numerical simulations of plasmonic and optical enhancement property were studied by using three-dimensional finite-difference time-domain (3D-FDTD) method with FDTD software package from Lumerical Solutions, Inc.. The x-axis polarized electromagnetic Gaussian wave was set to propagate normal to the substrate (-z direction). All boundary conditions were set to be perfect matching layer to eliminate any interference from the boundaries. The profile is modeled from the observation of SEM image. The electric field result observed in this paper is at x-z plane at y = 0 and the mesh size was set as 1 nm^3.

Raman spectroscopy measurement

Renishaw PL/Raman micro-spectroscope system was used in this paper for enhanced Raman signal measurements. 633 nm He-Ne laser was used as excitation light sources. 20X objective lens was used to focus/collect incident light and Raman signal onto/from the surface of NASERS devices.

DISCUSSION

FDTD simulation results of nanojet and plasmonic enhancement

The FDTD simulations results of enhancement effect due to nanojet and plasmonic substrate are demonstrated in figure 2. Firstly a Guassian beam was set to propagate to a 5 μm SiO_2 microsphere. The waist of beam was set to be 3.03 μm to fit the spot size of focused laser through objective lens in the Raman measurement. The focal plane was set at the center of the microsphere. As figure 2 (a) shown, a 3D confinement of electric field was generated as nanojet effect and the diameter of the confined beam is about 1 μm. Figure 2 (b) and (c) shows the comparison between plasmonic nanostructured SERS substrate with and without the presence of microsphere. It can be observed that the electric field was amplified significant by around two orders with the nanojet effect. It indicates that the dramatic increase of near field by adding the microsphere is expected to contribute higher enhancement to the Raman signal.

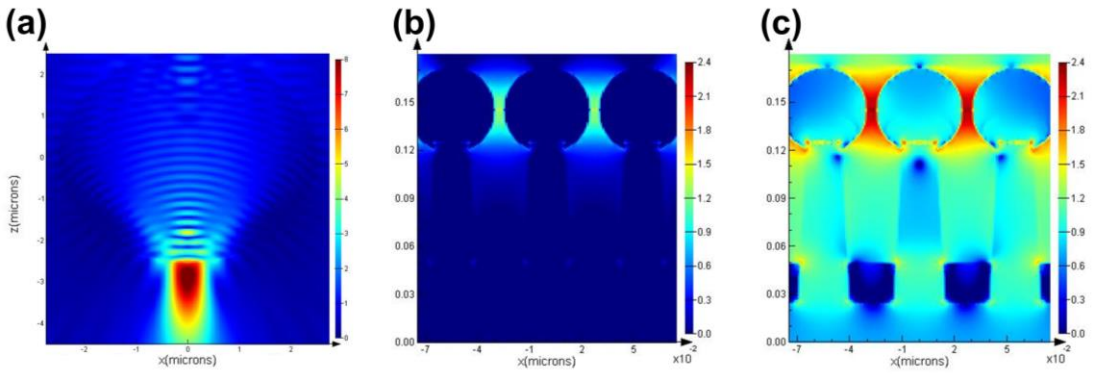

Figure 2. (a) Electric field distribution of nanojet confinement by propagating a Gaussian beam into a 5 μm SiO2 microsphere; (b) and (c) logarithm electric field distribution of nanostructured SERS substrate without and with the presence of microsphere

Results of Raman Spectroscopy

Firstly the experimental effect of nanojet enhancement to nanostructured SERS substrate was investigated. The targeted molecule used here was 1,2-bis(4-pyridyl)ethylene (BPE, Sigma-Aldrich). The substrate was immersed in 5 mM BPE ethanolic solution for 24 hours and then rinsed with pure ethanol solution to wash out extra BPE molecules stacked on the monolayer. Finally substrate was blown with nitrogen gas to completely dry. Figure 3 (a) shows the enhancement comparison of BPE Raman spectrum with and without microsphere. It can be observed that the nanojet effect from microsphere contributes a significant higher Raman enhancement by 5 times. Nevertheless, since the nanojet provides confinement phenomenon of incident field, the actual number of targeted molecule is greatly decreased. The enhancement from nanojet effect is approximately 183 times.

In order to perform single molecule detection, Rhodamine 6G (R6G, Sigma-Aldrich), which is a commonly used dye for low concentration detection, has been applied here as targeted molecule. Firstly the SERS performance of only nanostructure SERS substrate is evaluated and the Raman spectra of different concentrations of R6G are shown in Figure 3 (b). The Raman peaks from R6G can still be identified when the concentration is down to 10^{-8} M. Figure 3 (c) shows the Raman spectrum after adding microsphere onto the nanostructured SERS substrate. Under low concentration condition, the Raman spectrum is slightly different than the one with higher concentration. It has also been observed in other literature. [17, 18] It can be observed that prominent peaks can still be identified even the concentration of R6G is down to 10^{-12} M, which is very close to the single molecule detection if the confinement of incident field is considered.

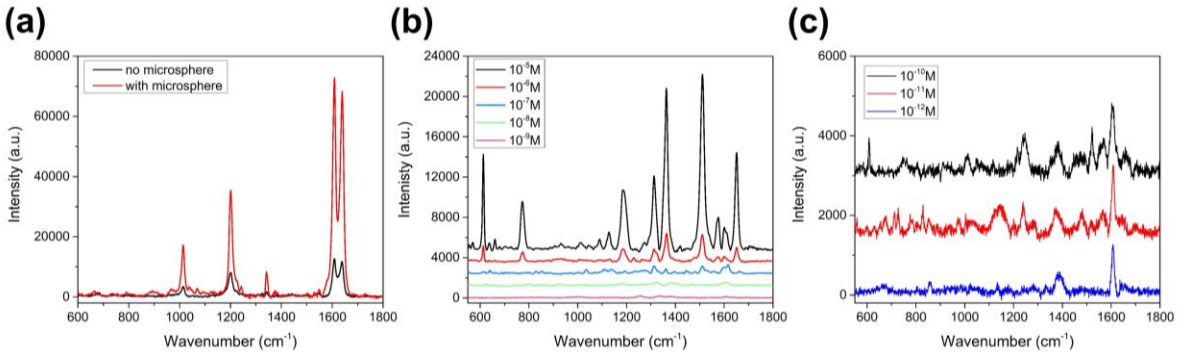

Figure 3. (a) The comparison of BPE Raman spectra with and without the presence of microsphere; (b) The Raman spectra of different concentration (10^{-5} to 10^{-9} M) measured with only nanostructured SERS substrate; (c) The Raman spectra of different concentration (10^{-10} to 10^{-12} M) measured with NASERS setup.

CONCLUSIONS

The nanojet and surface enhanced Raman spectroscopy (NASERS) has been demonstrated. With the combination of optical confinement from nanojet and plasmonic amplification from nanostructured metal surface, the near field is significant amplified according to the FDTD simulation results. This phenomenon is also experimentally demonstrated and the enhancement of combing nanojet effect with traditional SERS technique is calculated as 183 times compared to traditional SERS method. The low concentration detection of R6G has been performed and the limit of detection achievable by NASERS is down to 10^{-12} M, which is near single molecule detection level. This setup provides a simple but effective method to boost the Raman enhancement on current SERS technique by two orders of magnitude. This additional enhancement can be crucial for ultralow concentration detection such as single molecule detection by nanostructured solid SERS substrate.

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