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DOI: <https://doi.org/10.1016/j.saa.2019.05.018>

Reference: SAA 17113

To appear in: *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*

Received date: 1 March 2019

Revised date: 5 May 2019

Accepted
date: 9 May 2019

Please cite this article as: S. Yan, F. Chu, H. Zhang, et al., Rapid, one-step preparation of SERS substrate in microfluidic channel for detection of molecules and heavy metal ions, *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, <https://doi.org/10.1016/j.saa.2019.05.018>

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Rapid, one-step preparation of SERS substrate in microfluidic channel for detection of molecules and heavy metal ions

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Abstract

On-chip fabrication of surface-enhanced Raman spectroscopy (SERS)-active materials enables continuous, real-time sensing of targets in the microfluidic chip. However, the current techniques require the time-consuming, complicated process and costly, bulky facilities. In this work, we present a novel method for synthesis of Ag nanostructures in a microfluidic channel *via* one-step electroless galvanic replacement reaction. The whole reaction could be achieved less than 10 min, while the traditional methods take hours. The microfluidic channel has a Cu base, which can reduce Ag ions to Ag nanoparticles in the presence of AgNO₃ solution. The new technique enables the label-free sensing of chemical molecules (*i.e.*, methylene blue) and biomolecules (*i.e.*, urea). Two proof-of-concept experiments are performed to verify the utilization of the prepared SERS substrate. First, the microfluidics-assisted SERS sensor is used to detect Hg ions in aqueous solution with high sensitivity and good selectivity. Second, the fabricated SERS-active material can couple with a concentration gradient generator for continuous SERS detection. This simple technique can be used in any laboratory without any bulky equipment and can realize numerous lab-on-a-chip applications with the integration of other microfluidic networks.

Keywords: Microfluidics; Surface-enhanced Raman spectroscopy; Nanoparticle synthesis; Biosensor; Heavy metal detection

1. Introduction

Raman spectroscopy provides the fingerprint spectra that enable label-free sensing of molecules [1-2]. However, the overall intensities of Raman scattering signals are either too weak or are hard to realize the multiplexed sensing due to the low spectral resolution [3]. There is a demand to develop *in situ* techniques that can detect

molecules with ultrahigh sensitivity and high spectral resolution. Surface-enhanced Raman spectroscopy (SERS) [4-5] is one such technique with high sensitivity to detect targets on the single-molecule level on the surface with coinage-metal (*e.g.*, Au, Ag and Cu) nanostructures [6-7]. SERS spectra of molecules are enhanced 10^{10} to 10^{11} times over Raman signals [8]. The SERS enhancement is attributed to localized surface plasmon resonances (LSPR) of coinage-metal nanostructures [9-10]. SERS-based detection has been widely used in numerous research fields including environmental science [11], medicine [12-14] and cell biology [15-16].

Continuous SERS detection can be realized when SERS is coupled with a microfluidic channel [17-19]. To obtain the SERS-integrated microfluidic platform, the SERS active materials should be fabricated inside the microfluidic channel. Several deposition methods have been developed to fabricate the SERS-active metallic nanostructures, such as E-beam evaporator [20-21], laser deposition [22-23], Langmuir–Blodgett techniques [24], and thermal evaporation [25]. However, the deposition methods should be conducted under high-vacuum and high-temperature conditions using bulky, expensive facilities [26]. To generate the metallic nanostructures, lithography or post-treatment (*e.g.*, annealing [25] and plasma treatment [27]) is involved, which also makes the fabrication complicated.

On-chip fabrication of SERS-active materials is a facile approach that integrates the nanostructure formation and SERS detection without lithography or annealing. One of such techniques is laser direct writing [28], which fabricates the Ag SERS substrates via photo-reduction of silver ions. The Ag substrates could be precisely located by controlling the focused laser point. However, the laser direct writing requires femtosecond laser source and extra optical elements for laser focusing. The polyol method is another method, enabling the on-chip fabrication of SERS materials [27, 29]. The polyols can act as the solvent and the reducing agent for the metal ions [30]. The process is normally carried out at high temperatures and the involvement of polyols might bring the disturbance during SERS measurement.

Here, we report a method that can synthesize Ag nanostructures in the microfluidic channel via electroless galvanic displacement reaction between Ag and Cu. To our best knowledge, the reported methods [21, 23] to fabricate SERS substrate using galvanic displacement reaction always involve bulky equipment (*e.g.*, e-beam evaporator and femtosecond laser micro-machining system) and complex procedures (*e.g.*, electrodeposition, wet etching and annealing). However, the proposed method for fabrication of SERS substrate does not require complicated fabrication process and costly facilities, and can be achieved at room temperature and atmospheric pressure. No contamination is involved during the fabrication due to the absence of polyols. The microfluidic channel can not only assist the fabrication of metallic nanostructure, but also form continuous flow for SERS detection. The capability of this method to detect solutions containing methylene blue (MB) and urea is verified. Furthermore, we demonstrate that the microfluidics-assisted SERS sensor can be applied for monitoring the water pollution by detection of Hg ions. With the integration of a concentration gradient generator, the fabricated SERS materials can realize label-free SERS detection.

2 Materials and methods

2.1 Chemicals and reagents

The materials for fabrication of metallic nanostructures include AgNO_3 (Aladdin), ethanol (Aladdin), copper tape (3J), H_2SO_4 (Aladdin) and HAuCl_4 (Aladdin). The molecules used for the SERS measurement include Methylene blue (Aladdin) and urea (Aladdin). The chemicals for sensing selectivity of Hg (II) against other metal species include HgCl_2 (Aladdin), NaCl (Aladdin), CaCl_2 (Aladdin), CuCl_2 (Aladdin), BaCl_2 (Aladdin), and CdCl_2 (Aladdin). Except for HgCl_2 , the other metal salts have the same concentration of 1×10^{-4} M. NaBH_4 (Aladdin) is added to all the metal ion solutions in the selectivity test.

2.2 Instrumentation

Energy dispersive X-ray spectroscopy (EDS) was performed with a FE-TEM system (JSM-7800F, Joel). Scanning electron microscopy (SEM) images were taken to view the surface morphologies of the Ag nanostructures by using a scanning electron microscope (Mira 3 FE-SEM, Tescan).

2.3 Fabrication of microfluidics-assisted SERS sensor

The development of microfluidics-assisted SERS sensor involves two main steps: (i) bonding PDMS channel onto the copper tape, and (ii) forming Ag thin film *via* galvanic replacement reaction at room temperature (Fig. 1a). The SU-8 mold for microfluidic channels was fabricated using conventional photolithography (SU-8 2050, MicroChem, 50 μm thickness) [31-33]. A PDMS mixture (Sylgard 184, Dow Corning) was prepared and casted on the SU-8 mold to form PDMS channel (Fig. 1b). The microfluidic channel was 200 μm wide and 14 mm long. Next, the inlet and outlet were punched on the PDMS slab via 22G needle. The thickness of PDMS is about 2 mm. The PDMS channel and copper tape attached on a glass substrate were treated with oxygen plasma for permanent bonding (Fig. 1c). Though the bonding strength between PDMS and copper is not stronger than the conventional siloxane bond [34] between PDMS and glass, we did not observe the leakage with flow rate as high as 50 $\mu\text{L min}^{-1}$, which is sufficient to generate steady flow in microfluidic channel for SERS substrate fabrication and detection. Then, 2% H_2SO_4 solution was introduced into the microfluidic channel to remove the oxidation of copper tape at a flow rate of 20 $\mu\text{L min}^{-1}$ *via* a syringe pump (LSP02-1B, Longer Pump), following by the 2 mM AgNO_3 solution with the flow rate of 10 $\mu\text{L min}^{-1}$. Since the standard electrochemical potential of Cu (0.34V) is lower than that of Ag (0.80V) [35], Ag^+ could be reduced to Ag atom by receiving electrons from copper tape when the AgNO_3 solution was injected into the microfluidic channel with Cu base. The Ag nuclei formed on the Cu surface grow into Ag nanoparticles under the continuous-flow of AgNO_3 solution. Due to the spatial confinement of the microfluidic channel, Ag nanostructures only forms on the bottom of the channel, that is, on the surface of Cu substrate within the microfluidic channel (Fig. 1d). The obtained Ag film is then cleaned with ethanol at a flow rate of 40 $\mu\text{L min}^{-1}$. Further, the target molecules can be introduced for SERS detection. As for the acquisition of

SERS signals, a helium-neon laser (632.8 nm, Melles Griot) and a spectrometer (iHR550, Horiba, equipped with a charge-coupled device camera) were integrated to an inverted microscope (IX73, Olympus). The excitation and collection of light were done by a 50 $\times$ objective lens (NA 0.5). The proposed method for fabrication of SERS substrate within a microfluidic channel is simple and low cost, which avoids the high-temperature particle synthesis and complicated fabrication processes. Furthermore, the SERS material (Ag nanostructures) can be newly produced prior to each experiment due to the ease of fabrication, which circumvents the adverse effect of the oxidation of Ag nanostructures. Our proposed method is not limited to the on-chip fabrication of Ag nanostructures. By introducing the HAuCl₄ solution into the microfluidic channel, the Au nanostructures can be produced for SERS sensing (Fig. S1).

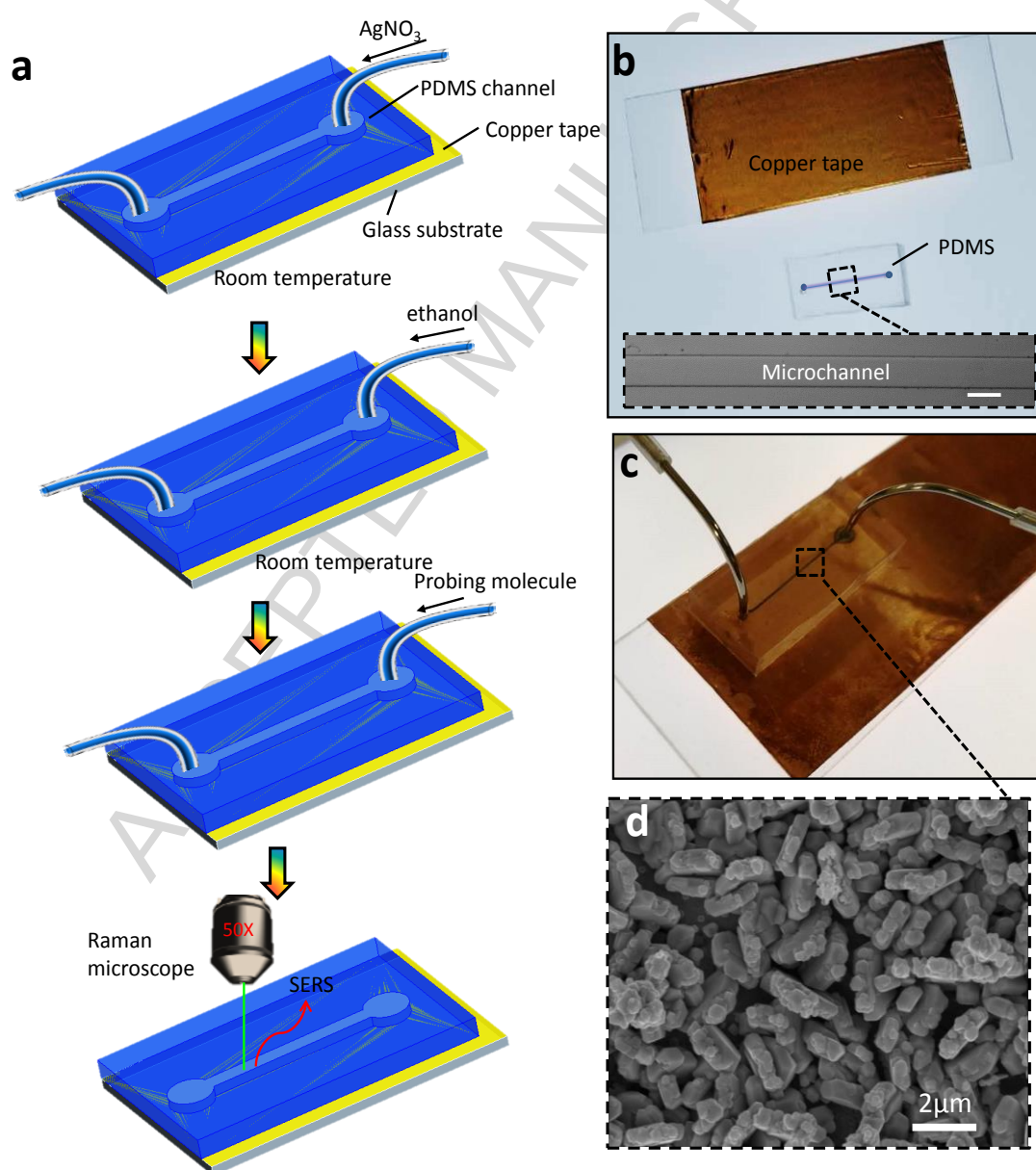


Figure 1 (a) A schematic of microfluidics-assisted SERS sensor. The Ag nanostructures were

obtained inside the microfluidic channel *via* electroless galvanic replacement reaction. After washing by the ethanol, the probing molecules were introduced for SERS detection. (b) A photograph showing the components of microfluidics-assisted SERS sensor, consisting of a PDMS channel and Cu base. The inset is the optical graph of the microfluidic channel. The scale bar is 200 μm . (c) A photograph of the assembled device. (d) SEM image of fabricated Ag nanostructures in a channel.

3. Results and discussion

3.1 Ag nanostructures along the microfluidic channel for SERS detection

In the microfluidic channel, the formation of Ag nanostructures commences when the AgNO_3 solution contacts the Cu surface at the inlet. Therefore, the concentration of Ag^+ reduced along the channel length due to the reduction of Ag^+ . Interestingly, due to the concentration gradient of Ag^+ along the channel, the Ag nanoparticles with different physical dimensions were synthesized in the same channel. The changed morphology of Ag nanostructures along the channel will, in turn, affect the SERS signals of a target molecule. The SERS phenomenon of a target molecule originates from an intense local electromagnetic field of Ag nanostructures [27]. First, we investigated the Raman intensities along the channel. Two microfluidic SERS channels were prepared (Fig. 2a and b). For channel I, AgNO_3 solution was injected into the channel with the single directional flow (inlet $\rightarrow$ outlet). The injection time of AgNO_3 solution was 4 min. For channel II, AgNO_3 solution was injected into the channel with the bidirectional flow (inlet $\rightarrow$ outlet, 2min, outlet $\rightarrow$ inlet, 2min). After washing, the target molecule, methylene blue (MB, 1×10^{-5} M), was introduced into the microfluidic channel for SERS measurements. The SERS signals were obtained at 8 points at the interval of 2 mm from the inlet to outlet of the channel. Six measurements at each point were acquired to calculate the average intensity and deviation. The 1618 cm^{-1} peak of MB was used for analysis. The Raman scattering of PDMS will not affect the SERS measurement because it is inherently weak compared to the SERS signals of molecules (Fig. S2).

As for the channel I, the Raman intensity was the highest at the point 2 mm from the inlet and then decreased along the channel. The Raman intensity at the outlet is 5 times lower than that at the highest intensity region (2 mm from inlet). Since the SERS intensity decreases dramatically with the increase of the particle gap [36], the poor SERS performance at the outlet attributes to the larger particle gaps. The lower Ag^+ concentration at the outlet will lead to the smaller Ag nanoparticles and larger particle gaps, as evidenced by scanning electron microscope (SEM) images in Fig. 2c. At 2 mm, the smallest particle gap was observed from SEM images, which verified the highest Raman intensity. Although the highest Ag^+ concentration occurs at the inlet (0 mm), the dense and irregular nanostructures with large holes lead to relatively low Raman intensity. As for channel II, the Raman intensity is also highest in this case at the point of 2 mm from the inlet. However, another peak occurs at the point of 12 mm with the bidirectional flows. When the AgNO_3 solution is perfused from the outlet, the fresh Ag^+ will be reduced to Ag nanoparticles at the outlet region, causing the improved SERS intensity. With the bidirectional perfusion, we can always obtain

the high SERS intensity at the point of 2 mm from the perfusion ports. Thus, the optimal working region for effective SERS detection is at the point of 2 mm from the perfusion port.

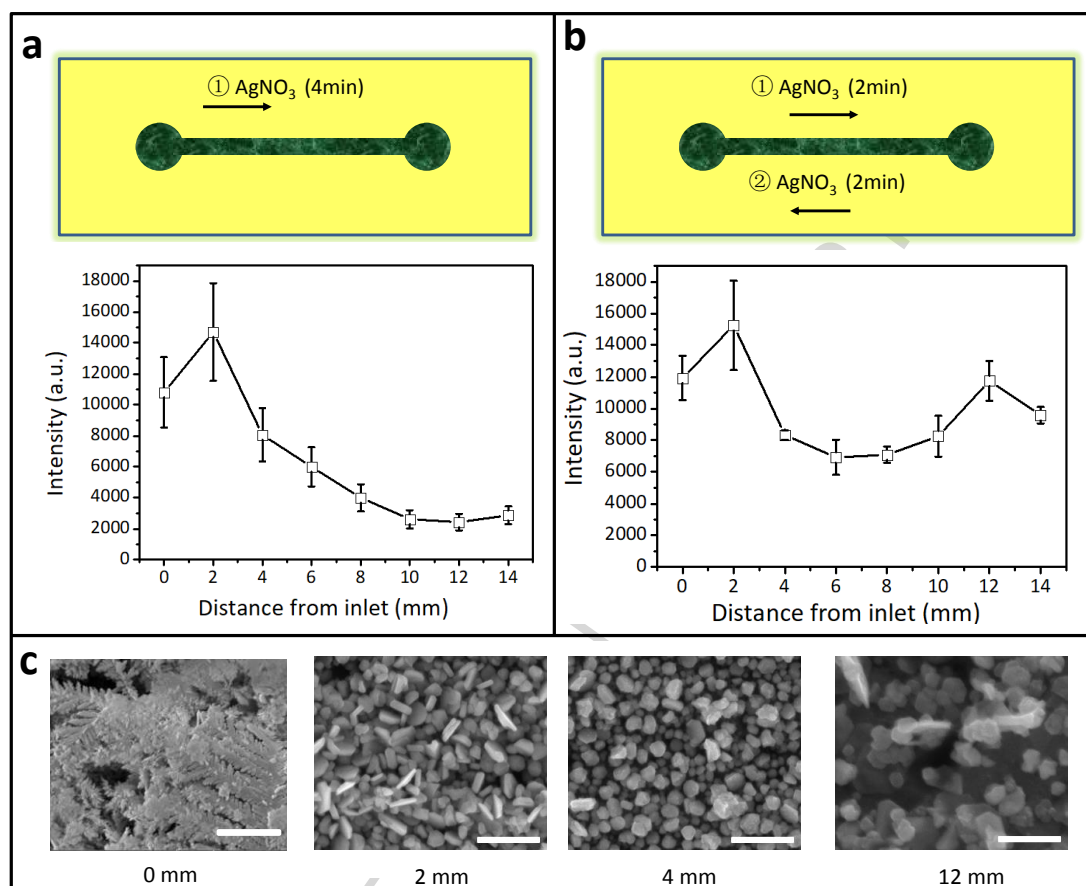


Figure 2 (a) The variation in SERS intensity of MB at 1618 cm^{-1} versus the distance from the inlet port. The AgNO_3 solution was introduced into the channel from inlet port for 4 min. (b) The variation in SERS intensity of MB at 1618 cm^{-1} versus the distance from the inlet port. The AgNO_3 solution was injected into the channel with the bidirectional flow (inlet→outlet, 2min, outlet→inlet, 2min). (c) SEM images showing the morphologies of Ag nanostructures along the microfluidic channel. The scale bar is 500 nm.

3.2 SERS detection of MB with various concentrations

To further investigate the sensing capability of microfluidics-assisted SERS sensor, we tested the devices using MB solutions with different concentrations, ranging from $1 \times 10^{-8}\text{ M}$ to $1 \times 10^{-4}\text{ M}$. The SERS measurements were performed at the point of 2 mm from the inlet port to obtain the highest Raman intensities. Fig. 3a showed the SERS signals of MB with 5 different concentrations. The characteristic peaks of MB were apparently identified in all spectra, and the peak intensities reduced with the decrease of MB concentration. Once the MB solution was diluted to $1 \times 10^{-8}\text{ M}$, all of the characteristic peaks of MB were lost. Therefore, the limit of detection (LOD) of this microfluidics-assisted SERS sensor was $1 \times 10^{-7}\text{ M}$. To verify the obtained signals were SERS phenomenon rather than normal Raman scattering,

another microfluidic channel without the process of the galvanic reaction was prepared. Without the Ag nanostructures, the Raman scattering signal could hardly be observed at the concentration of 1×10^{-5} M (Fig. 3b), which demonstrates that all the peaks came from SERS. The enhancement factor (EF) is a key parameter to evaluate the amplification of SERS devices. The definition equation for enhancement factor (EF) applied to the case of in-channel SERS is described as [21]: $EF = (I_{\text{SERS}}/C_{\text{SERS}})/(I_{\text{NR}}/C_{\text{NR}})$. Where I_{SERS} represents the intensity of the SERS signal; I_{NR} is the intensity of the Raman signal on a silicon substrate; C_{SERS} and C_{NR} are the concentration of molecules contributing to I_{SERS} and I_{NR} , respectively. Using the SERS intensity at 1618 cm^{-1} for 1×10^{-5} M MB in Fig. 3a and the corresponding intensity of 0.39 M MB on a non-enhanced Raman substrate (*e.g.*, Si), the calculated EF is about 1×10^6 .

Most of the current SERS techniques require the evaporation of solute prior to the SERS measurements [37-38]. The dried analytes adhere to the SERS substrates and are hard to be washed away, which limits the repeatability of SERS substrates. However, the microfluidics assisted SERS platform can be repeatedly used to detect the target molecules adhered to the SERS substrate by physical adsorption. Since the MB can be attached to the SERS substrate *via* physical adsorption, the adsorbed MB can be cleaned by ethanol. As shown in Fig. 3c, the first SERS measurement was MB with the concentration of 1×10^{-5} M. After on-chip washing by the ethanol for 10 min, no SERS signal was observed at the second measurement. Then, MB with the concentration of 1×10^{-6} M was introduced into the microfluidic channel for the third SERS measurement. The obtained SERS signal of MB was disappeared again after washing, which validated that our microfluidics assisted SERS sensor can be repeatedly used for SERS detection of molecules on SERS substrate *via* physical adsorption.

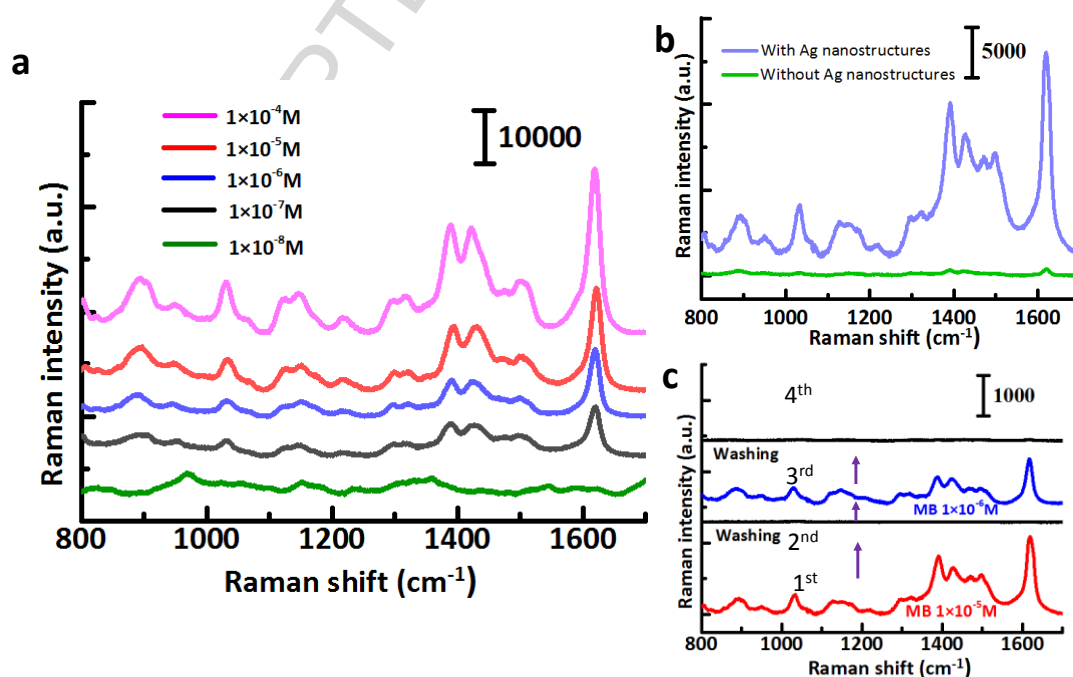


Figure 3 (a) Concentration dependent SERS spectra of MB measured in the microfluidics assisted

SERS sensor. The concentration ranges from 1×10^{-8} M to 1×10^{-4} M. (b) Spectra comparison of MB at the concentration of 1×10^{-5} M in a channel with Ag nanostructures and a channel without Ag nanostructures. (c) SERS spectra showing the reproducibility of the microfluidics assisted SERS sensor.

3.3 SERS detection of biomolecules

To demonstrate the biocompatibility of microfluidics assisted SERS sensor, a biomolecule (*i.e.*, urea) was utilized as target to characterize the device. Urea, a metabolite, mainly exists in human blood and urine. The detection of urea is of great significance in monitoring of kidney function. Here, urea solution was prepared at the concentrations of 1×10^{-5} M, 1×10^{-4} M, 5×10^{-4} M, 1×10^{-3} M, and 1×10^{-2} M and then injected into the microfluidic channel using a syringe pump. The SERS measurements were obtained at the point of 2 mm from the inlet. After each concentration measurement, the channel was rinsed with ethanol to remove the residue molecule. Fig. 4 presented SERS spectra of urea solutions in the microfluidics-assisted SERS sensor. A characteristic peak of 1000 cm^{-1} was observed, which corresponded to the symmetrical C-N stretching vibration mode [39]. As previously reported SERS sensors of urea detection, the LOD of Au-coated nano-dome arrays was 11.9 mM [40] and LOD of nanoporous gold disk arrays was 0.67 mM [41]. Our device with the LOD of 0.1 mM has higher sensitivity for clinical applications such as kidney function monitoring and urine analysis.

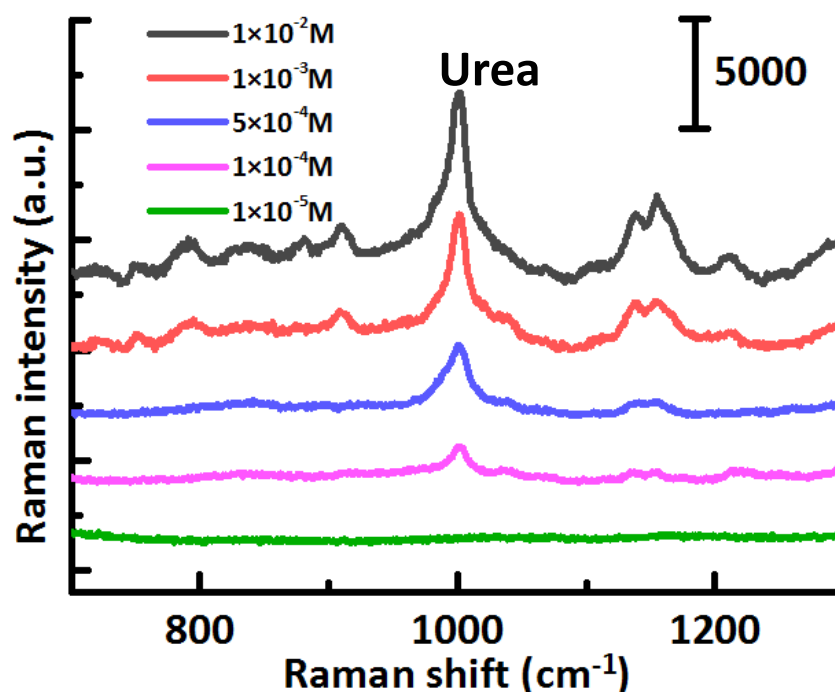


Figure 4 Concentration dependent SERS spectra of urea measured in the microfluidics-assisted SERS sensor. The concentration ranges from 1×10^{-5} M to 1×10^{-2} M.

3.4 Mercury (II) detection

Except for the application in the detection of biomolecules, the microfluidics assisted SERS sensor can also be utilized to detect the Hg (II) for environmental monitoring and evaluation of wastewater treatment. Hg (II) is toxic to human beings and animals, even at low concentrations. Currently, there are two SERS-based methods for detection of Hg (II) in solutions. The first one is that Hg (II) links a Raman probe (*e.g.*, DNA enzyme [42] or T-Hg²⁺-T pairs [43]). With the increase of Hg (II) concentration, the SERS intensities of marker molecules also increase, which can detect the Hg (II). The second method is based on the amalgamation of Hg (II) with the SERS active metal nanoparticles [44]. With the reduction of Hg (II) into Hg (0) on the surface of nanoparticles to form Hg/Ag shell (Fig. 5a), the SERS intensities associated with the Raman marker molecules will decrease. Based on this phenomenon, the Hg (II) could be detected in the microfluidics assisted SERS sensor with Ag nanostructures.

The microfluidics assisted SERS sensor was prepared using the same method described before. The Hg (II) solutions with various concentrations (1×10^{-9} M to 1×10^{-3} M) were separately introduced into the channel for 10 min. The addition of sodium borohydride (NaBH₄) in Hg (II) solutions could accelerate the amalgamation process [45]. The Hg amalgamation was further verified by the energy dispersive X-ray spectroscopy (EDS), as evidenced by Fig. 5b. The substrate consisted of Cu (copper base), Ag and Hg. Thus, Hg was reduced on the Ag nanostructures. Then, the MB at the concentration of 1×10^{-5} M was pumped into the channel, acting as a Raman marker. The 1618 cm⁻¹ peak of MB collected in different concentrations of Hg (II) was analyzed to evaluate the sensitivity of our device in detecting Hg (II). The relation between the concentration of Hg (II) and the corresponding SERS intensities was plotted in Fig. 5c. Three phases were observed in the change of SERS intensity with the increasing concentration of Hg (II). In the first phase, Hg (II) at very low concentration ($< 1 \times 10^{-8}$ M) did not affect the SERS intensities of Raman markers due to the weak interaction between Hg (II) and Ag nanostructures. In the second phase, when the Hg (II) was higher than 1×10^{-7} M, a dramatic decrease in the SERS intensity with the increase of Hg (II) concentration was observed. This was attributed to the formation of Hg/Ag shell on the Ag nanostructures, which influenced the LSPR of Ag nanostructures. In the last phase, almost no SERS signal was observed. The LOD of our device for detection of Hg (II) is 1×10^{-7} M because the SERS intensity begins to decrease when the Hg (II) in aqueous solution is over 1×10^{-7} M. To improve the detection limit, colloidal lithography may be used to obtain the more uniform metallic nanostructures [46-48].

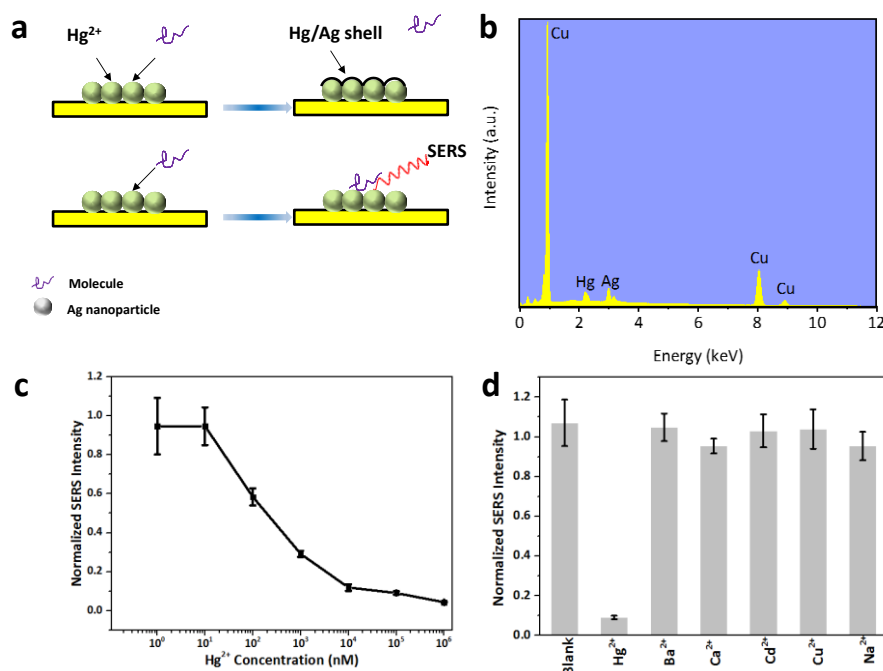


Figure 5 (a) Schematic description of the detection of Hg (II) on the Ag particles. (b) EDS data of SERS-active substrate. The substrate consists of Cu (base), Hg, and Ag. (c) The normalized SERS intensity of the peak at 1618 cm^{-1} versus the Hg (II) concentration. (d) The selectivity of the proposed SERS detection Hg (II) against other metal ions. Each measurement was repeated three times.

Our microfluidics assisted SERS sensor also has good selectivity in the detection of Hg (II). As shown in Fig. 5d, five divalent metal ions are used and none of them can reduce the SERS intensity as much as that induced by Hg (II), demonstrating that the proposed method has great potential to detect the contamination of Hg (II) in aquatic ecosystems.

3.5 SERS detection in the concentration gradient generator

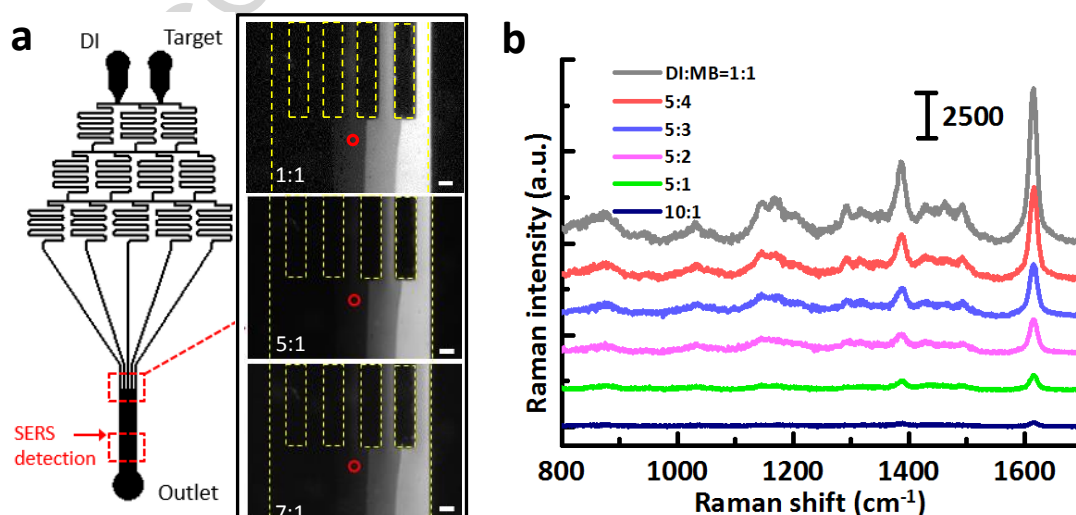


Figure 6 (a) SERS detection of molecules in the concentration gradient generator. DI water and the target molecules can spatially generate the concentration gradient through the “Christmas tree” channel as shown in the fluorescent images. By varying the flow rate ratio, the concentration at the same location can be changed. (b) The SERS intensity of MB molecules gradually increases with the decrease of the flow rate ratio of DI water and MB solution.

The microfluidics assisted SERS sensor could achieve more complex functions by integrating with an advanced microfluidic channel. Here, a “Christmas tree” channel was designed, which could generate the spatial concentration gradient by fluidic mixing [49], as shown in Fig. 6a. The channel had two inlets and one outlet. In this experiment, the AgNO_3 solution was introduced into the channel *via* outlet port to form the Ag nanostructures, as described above. The DI water and the target molecule – MB as a test sample were injected through the left side inlet and right side inlet, respectively. The flow rate of DI water was set to be constant ($10 \mu\text{L min}^{-1}$). By varying the flow rate of the target molecule, the concentration gradient can be dynamically changed. To visualize the concentration gradient in the channel, the fluorescent molecule, Rhodamine B, was pumped into the channel. The images were taken under the fluorescent field (Fig. 6a). The two inlets were divided into five channels through a three-level structure. The concentration gradient was successfully formed after the fluids passed mixing units and then merged into a single channel. The fluorescent intensity at the red circle was decreased when the flow rate of dopamine solution was reduced from $5 \mu\text{L min}^{-1}$ to $1 \mu\text{L min}^{-1}$. Based on this mechanism, we could detect the non-fluorescent molecules with the integration of SERS. The MB at the concentration of $1 \times 10^{-5} \text{ M}$ was pumped into the channel *via* the right-side inlet. The SERS measurement was also done at the same location (middle of the channel) but with a different flow rate of MB. The flow rate ratio of DI water and the MB solution was varied from 10:1 to 1:1. The SERS signal with the main peak of MB at 1618 cm^{-1} was clearly observed from the experiments and increased with the increase of flow rate of MB solution (Fig. 6b). This experiment demonstrates that the SERS substrate is able to detect the molecules with the integration of a concentration gradient generator. The good compatibility with other microfluidic networks enables the microfluidics assisted SERS sensor to achieve diverse functions.

Conclusions

This work described a simple, microfluidics-assisted method to fabricate the SERS-active materials. The silver nanostructures were prepared inside the microfluidic channel *via* one-step electroless galvanic replacement reaction. The various particle sizes were obtained along the microfluidic channel and the point of 2 mm from the inlet port was found to produce the highest Raman signal. The microfluidics-assisted SERS sensor had been demonstrated its capability to detect the chemical molecule (*e.g.*, MB) and biomolecules (*e.g.*, urea). The microfluidics assisted SERS sensor was further used to detect the Hg ions in the aqueous solution, which showed LOD of $1 \times 10^{-7} \text{ M}$ and good selectivity against other metal ions. In addition, a proof-of-concept experiment was developed to show that our method could

realize SERS detection with the integration of a concentration gradient generator.

The developed microfluidics-assisted SERS sensor has several advantages. First, this platform can integrate the nanoparticle synthesis, fluidic introduction, and SERS detection in a single chip. Second, the microfluidic channel can spatially and temporally confine the fluids into the small area. Due to this unique property, the different particle size can be produced in the process of particle synthesis *via* electroless galvanic reaction. The molecules were introduced to the channel with the exact alignment with the SERS substrate. Third, the device can be repeatedly used for SERS detection of molecules on the SERS substrate *via* physical adsorption. Last, the microfluidics-assisted SERS sensor can couple with a concentration gradient generator to form a label-free sensing system. We envision that our proposed technique can achieve diverse functions for lab-on-a-chip applications by integrating with other microfluidic networks.

Conflicts of interest

There are no conflicts of interest to declare.

Authors' contributions

SY, FC, HZ and YY conducted the experiments. SY, SL, and WW contributed most of the ideas and supervised all experiments and theory. SY, SL, WL, and WW wrote the paper. YH, SW, AL conducted the material characterization. All authors discussed the results and commented on the manuscript. All authors read and approved the final manuscript.

Acknowledgements

Dr. Sheng Yan is the recipient of the 2018 Endeavour Research Fellowship funded by the Australian Department of Education and Training. Prof. Wang and Prof. Huang thank the support from the Fundamental Research Funds for the Central Universities (2018CDXYWU0025, 2018CDJDWL0011). Dr. Li would like to thank the financial support by 'Shenzhen Peacock Plan' (No. KQTD2016022614361432) and Fundamental Research Funds for the Central Universities (2018CDXYGD0017). Prof. Liu would like to thank the financial support by the National Natural Science Foundation of China (No. 61575033).

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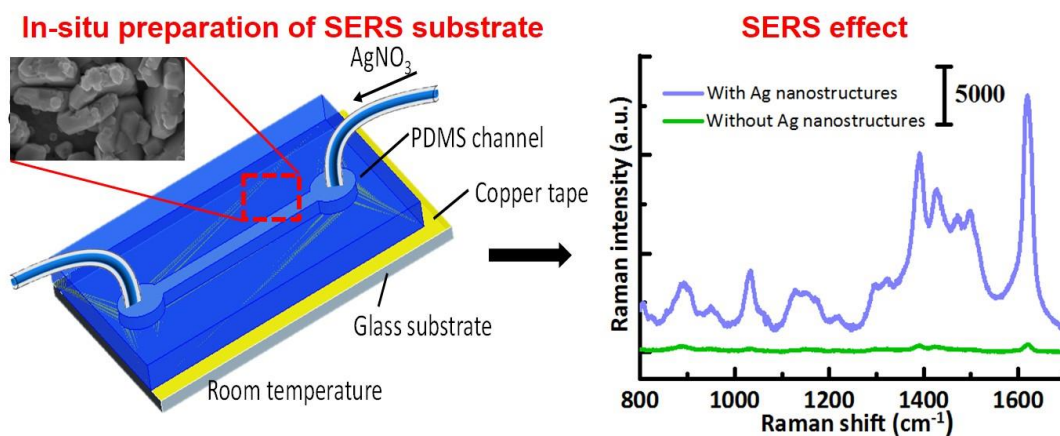
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Graphical abstract

Highlights

- A microfluidics assisted technology for on-chip preparation of Ag nanoparticles for SERS substrate with simple and low-cost process.
- Various molecules including methylene blue and urea were used to test the sensitivity and biocompatibility of the microfluidics assisted SERS sensor.
- Mercury detection with high sensitivity and good selectivity against other metal ions.
- Real-time SERS detection with the integration of the concentration gradient generator.