Four-step fabrication of SERS-active microfluidic channels

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Abstract. We present a technique to fabricate SERS substrates fully integrated with microfluidic channels. The fabrication of microsized dielectric channels was based on selective wet etching of a poled/unpoled silicate glass while silver nanoisland film was grown on the bottom of the channels via out-diffusion technique. Different combinations of fabrication steps were studied to optimize the channels’ depth, formation of the metal nanoislands and the roughness of the channels’ bottom.

1. Introduction

Surface enhanced Raman scattering (SERS) is a powerful analytical tool for label-free biological and chemical sensing [1, 2]. Because of a high sensitivity, this phenomenon is widely applied, in particular, in biomedicine, pharmacy analysis, food safety inspection and environment monitoring. SERS-active substrates can provide the enhancement of Raman signal as high as $10^8 - 10^{11}$ [3]. The prospective ones are large-scale ensembles of self-assembled metal nanoparticles (NPs) [4, 5]. Optically excited surface plasmon resonance in metal NPs increases local electric field of incident light-wave in their vicinity. In its turn, this E-field enhances Raman scattering from a sample medium adsorbed on the NPs ensembles’ surface.

Microfluidic chip is another perspective analytical tool widely used for chemical/biological sensing [6]. Devices based on microfluidics are able to sustain continues sampling of microliters of an analyte and solution mixing. The integration of SERS-active substrates with the microfluidic platform opens a way to in situ analysis of biological systems and chemical compounds [7]. The combination of the high speed of the analysis and minimal sample consumption is perfectly fulfilling the needs of aforementioned applications. Several implementations of the on-chip detection system were suggested by now. Among them are synthesized SERS-active colloids which are injected simultaneously with an analyte and mixed in glassy microfluidic channels [8] or lithographically made plasmonic structures (nanodisks [9], nanopillars [10] etc.) exploited in polymeric microfluidics. However, the controllable in situ fabrication of SERS-active substrates within microchannels is in demand [11, 12]. Here we present a new four-step technique for the in situ fabrication of glass microfluidic channels with SERS-active silver nanoisland film formed on the bottom of the channels.

2. Experimental

The channels were fabricated by chemical etching of a “Menzel” commercial soda-lime glass thermally poled with a profiled anodic electrode. The glassy-carbon electrode was patterned as a set of
650 nm deep periodic rectangle hollows separated by 200 µm gaps. The studied channels were 10, 30, 60 and 100 µm in width with the fixed length, 2000 µm. In the poling, while DC voltage of 300 V was applied at 300°C for 30 min to the 1 mm thick glass slide with pressed anodic and cathodic electrodes, positive ions of the glass were drifting from the glass anodic surface towards the depth. Finally, a depleted with the ions (poled) glass layer was formed, which thickness depended on the electric field strength. Since electric field in the glass region under the electrode hollows is weaker than in the regions of the electrode-glass contact, the poled layer in the regions under the hollows was thinner [13]. Etching of the samples in a polishing etchant, NH₄F:8H₂O, allowed forming of grooves (channels) in these regions due to the slower etching rate of poled comparatively to unpoled glass [14] and to the thinner poled layer under the hollows. The duration of the etching varied from 10 to 40 minutes. We used lasted for 20 minutes ion-exchange processing of the samples in AgNO₃(5 wt.%)/NaNO₃(95 wt.%) melt heated up to 325°C for doping the subsurface layer of the glass with silver ions. A silver nanoisland film was self-assembled on the samples’ surface via the reduction of silver ions penetrated into the samples. The reduction was performed via annealing the samples in hydrogen atmosphere at 250°C for 10 min. These steps are illustrated by figure 1a.

Three series of samples were fabricated with the change in the order of the aforementioned steps, as shown in figure 1b. We performed thermal poling, etching, ion-exchange of the sample 1 (S1), thermal poling, ion-exchange, etching of the sample 2 (S2), and ion-exchange, poling, etching of the sample 3 (S3). The formation of the nanoisland film via annealing was the last step, the same for all the samples. All sequences of these steps resulted in glass substrates with microsized channels with silver nanoisland film on their bottom. The dependence of the channels’ depth on the etching time (10, 20, 30 and 40 min) was studied using tip profilometer measurements (Dektak 150, Veeco). The bottom relief and the nanoparticles’ morphology in the channels etched for 10 min were characterized using atomic force microscope (AFM, Dimension 3100, Veeco) with RTESP tip and with scanning electron microscope (SEM, Leo 1550 Gemini, Oberkochen).

Figure 1. Schematics of the microfluidics channels fabrication: (a) thermal poling (P) with the structured electrode, wet etching (E) in the polishing etchant, silver-sodium ion-exchange (IE) and silver nanoisland film formation in hydrogen annealing (A). (b) Three routines of the samples fabrication and overall look of a substrate with microfluidic channels integrated with SERS-active layer.
3. Results and discussion

We studied the etching processing of the samples $S_1$ and $S_3$ series, assuming that the etching of the $S_2$ was similar to the $S_1$. Both $S_1$ and $S_2$ were firstly poled, which was the crucial glass modification resulted in selective etching as it is stated above. We etched the $S_1$ and $S_3$ samples for 10, 20, 30 and 40 min and measured the depth of the channels of 10, 30, 60 and 100 µm width prior the fabrication steps followed the etching. It should be noted that both poled (between the electrode hollow) and weaker poled/unpoled (under the electrode hollow) regions of the glass are etched in the processing. Thus, the measured depth of a channel is the difference of the thicknesses of the layers etched off between and under the hollows. When the thin poled layer under the hollows is completely etched off, the thicker layer between the hollows starts working as a mask because of a slower etching rate comparatively to the unpoled glass region beneath the hollow.

The results of the etching experiments are presented in figure 2a. One can see that the channels’ depth increased linearly with the etching time, while the channels in $S_3$ were generally deeper than in $S_1$, excluding the point corresponding to 10 min etching. The channels’ depth did not significantly change after the long lasting etching. The reason is that when in the etching the poled layer outside the channels was completely etched off, its masking effect disappeared and the etching rates in both areas outside and inside the channels became equal [14]. The maximal depth in $S_1$ was 0.9 µm (after 20 min etching) and in $S_3$ it was 1.3 µm (after 30 min etching).

![Figure 2](image.png)

**Figure 2.** (a) Temporal evolution of the channels depth in the course of the chemical etching. (b) The schematic explaining of the depth evolution, where $v_{\text{pol}}$, $v_{\text{ie-pol}}$, $v_{\text{glass}}$, $v_{\text{ie glass}}$ are the etching rates of poled, ion-exchanged and then poled, virgin and ion-exchanged glass, correspondingly.

We assume that the poled layers formed in the ion-exchanged glass ($S_3$) are more etching-resistant comparatively to ones formed in the virgin glass ($S_1$). This could be due to a lower mobility of silver ions in $S_3$ compared to alkali ones in $S_1$ and corresponding differences in the poling-induced restructuring of the poled regions of the ion-exchanged and virgin glasses. These differences could result in a longer time necessary to etch off a thin poled layer corresponding to the electrode hollow and, respectively, in the slower increase in the channel depth at the initial stage of the $S_3$ etching, up to
10 min. This consideration is illustrated in figure 2b. In longer etching, when the poled layer under the electrode hollow is completely etched off, lower etching rate of the poled ion-exchanged layer of the S3 out of the channel provides longer time of the removal of this layer, which corresponds to the longer masking effect, which is responsible for the selective etching of the channel bottom. This resulted in the deeper channel in S3. With the following increase of the etching duration, the complete removal of the poled layer out of the channels takes place both in S1 and S3. It is worth to note that here we do not account for possible difference in the etching rates of the virgin and ion-exchanged glasses. Besides, we did not find differences in the depth of channels of different widths in all the samples.

The AFM and SEM characterization of the S1-S3 samples was performed for 10 min etching only, corresponding images of the nanoisland films integrated with the 60 µm channels in S1-S3 samples are shown in figure 3. Silver nanoisland films on the bottom of the channels were observed in all the samples (see insets in figure 2a-c). Notably, the film in S3 treated as follows: ion-exchange – poling – etching – annealing, essentially differed from ones in S1 and S2. The fraction of area occupied by silver nanoparticles (fill factor) was 37% for S3 while only 18% and 17% for S1 and S2, respectively. The overall nanoislands’ shape was a truncated sphere however the average size, D, and polydispersity, σ, of the nanoislands were the highest for the S3 as well, 25 nm and 44%, correspondingly. The average sizes of the formed nanoislands in the S1 and S2 were 16 nm and 18 nm, while their polydispersity was 34%. The high density and NPs size of the film in the S3 (ion-exchanged prior the poling) indicates a higher silver content compared to S2 and S3 which had been firstly poled. The reason is a lack of alkali ions in the subsurface layer of the poled glass under the electrode hollow, which inhibits the ion-exchange processing. The nanoparticles did not grow outside the channels in all the samples (see figure 3d) because of the essential thickness of alkali/silver ions depleted layer formed under the strong electric field in the regions of the electrode-glass contact.

Figure 3. (a-c) SEM and AFM images of the 60 µm channels’ bottom in the samples S1-S3 etched for 10 min; (d) SEM and AFM images of the area outside the channel. Average size D, polydispersity σ, fill factor and roughness are denoted near corresponding images of the samples.

One can see in figure 3 that the relief of glass on the bottom of the channels differs in differently fabricated channels. The average roughness of the channels bottom was 180 nm in the S1, 120 nm in the S2 and 70 nm in the S3. Finally, processing order of the sample S3 has provided both formation of denser silver nanoisland film and smoother bottom of the etched channel.
4. Conclusions
We believe that ion-exchange – poling – etching – annealing order of glass slides processing is optimal for the formation of silver nanoparticles integrated into microfluidic channels. This four-step fabrication resulted in the formation of the silver nanoisland film with the highest fill factor, 37%, on the bottom of the microfluidic channel while the bottom was the smoothest, 70 nm roughness. Essentially, the nanoparticles did not grow outside the channels. We also found a difference in the depth of the channels formed in the differently treated samples. The maximal depth, 1.3 µm, has been registered after 30 min etching in the glass sample, which was ion-exchanged prior the thermal poling. The longer etching resulted in the stationary depth of the channels because of the complete removal of the poled layer of the glass outside the channels.

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