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Fabricating Plasmonic Components for Nano- and Meta-Photonics

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Abstract Different fabrication approaches for realization of metal-dielectric structures supporting propagating and localized surface plasmons are described including fabrication of nanophotonic waveguides and plasmonic nanoantennae.

1 Introduction

One of the main research goals in modern photonics is to find optimal configurations that can efficiently guide and strongly focus optical fields. Developing structures offering efficient propagation and strong localization of light opens up new application possibilities in sensing, nanoscale manipulation and optical characterization. One of the avenues in the field of compact photonic devices and nanophotonics that has recently attracted considerable interest is optics based on the controlled excitation of *surface plasmons* (SPs) [1–3]. SPs on metal-dielectric interfaces and metal nanoparticles are characterized by strong confinement of the electromagnetic field in the direction perpendicular to the metallic surface. This feature makes plasmonic structures very attractive candidates for developing new photonic components. Recently, resonant interactions in metal nanostructures involving both localized and propagating surface plasmons have been broadly investigated both theoretically and experimentally using nanostructures of different shapes and configurations. A variety of promising geometries for SP directional propagation, bending, focusing and localization have been reported [1–3].

Examples of metal-dielectric structures investigated for guiding and manipulation of SPs range from special configurations of nanoscatterers on metal surfaces

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[4, 5], chains of metal nanoparticles [6], metal strips with nm-scale thickness [7–11] and subwavelength metal nanowires [12, 13] to profiled metal surfaces [14–22]. Different geometries used to control the SP propagation are investigated with respect to the trade-off between confinement and loss [1], and the structure choice is further governed by the length scale over which energy is to be transferred and routed. One of the most promising directions in the area of plasmonic waveguides is investigation of profiled metal surfaces, namely grooves and wedges, as waveguides supporting strongly localized plasmon modes [14–23]. The requisite for the further development of such plasmonic components for real-life applications is availability of robust large scale manufacturing processes for making profiled and nanostructured metal-dielectric surfaces.

Equally advancing are studies of localized surface plasmons. Highly efficient, localized surface plasmon resonance of paired gold nanoparticles (optical nanoantennae) gives rise to significantly enhanced and highly confined electromagnetic fields that have a great importance for sensing and tagging applications, nanoscale lithography, and as the basis for nanolasers [24–29]. While very high intensity enhancements ($\geq 10^3$) have been reported (for example, for the experiments on surface enhanced Raman scattering (SERS) [29]) large variations in the resonant effects were observed for nominally identical structures due to the fact that SP resonance is strongly dependent on structural parameters, especially on the distance between the two interacting particles and their sizes. Thus, fabrication procedures that combine high reproducibility, robustness and ability of creating small interparticle gaps in a controlled way are required.

Over the last decades, modern nanofabrication techniques have opened new possibilities for controlling and preparing profiled and patterned metal surfaces in order to tailor the properties of excited surface plasmons. Fabrication of plasmonic structures requires development of robust processes that offer high reproducibility, low loss, and flexibility, and can be adaptable for different designs and applications. So far, one of the most frequently used techniques is *electron beam lithography* (EBL) that is widely used for manufacturing of different plasmonic components, see for example in [2, 4–6, 11, 13, 27]. However, if a large area has to be patterned (up to millimeters or centimeters in size) EBL-based fabrication becomes quite time-consuming, and therefore, expensive, which makes this technique not suitable for real device applications. Thus, there is a constant search for alternative high-throughput nanofabrication techniques that can be compatible with large-scale fabrication. For example, for plasmonic components based on nanostructured sub-wavelength thin metal strips where efficient gratings were first introduced via EBL [10, 11] a simple and cheap fabrication process compatible with *nanoimprint lithography* (NIL) was recently developed [30]. For creating various infinite and finite-area arrays of plasmonic nanoparticles, a high-throughput nanofabrication technique based on soft interference lithography that combines the ability of interference lithography [31] to produce wafer-scale nanopatterns with the versatility of soft lithography [32] was recently proposed for producing plasmonic nanostructures over tens of square centimetres [33].

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In addition to the high-throughput requirement, the choice of the optimal nanofabrication technique is also governed by the loss issue in plasmonic structures. It was reported that the surface roughness of fabricated metal-dielectric structures has an effect on the increased losses at the plasmon resonances [34]. Comparison of existing planar fabrication methods and chemical approaches also deserved a great deal of attention yielding important results on the issue of surface roughness that contributes to the SP loss [12].

Here, we focus on fabrication of metal-dielectric configurations supporting propagating and localized SP modes that requires development of nanoscale patterning tools and production-compatible techniques for structures with real-device applications potential.

2 Profiled Metal Surfaces as Plasmonic Waveguides

Coupling of SPs on opposite sidewalls of either a channel or wedge made in metal leads to formation of highly localized plasmonic modes that can be used for making compact optical components (Fig. 1).

(a) (b)

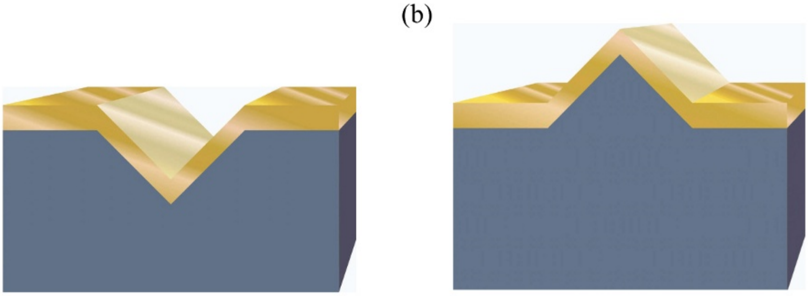

Fig. 1 Schematic of (**a**) a V-groove and (**b**) wedge made in metal. Both structures support plasmonic modes localized at and propagating along the groove bottom/wedge apex [14–20].

A V-shaped metal groove supporting a strongly localized plasmon-polariton mode (called *channel plasmon-polariton*, CPP) is of particular interest due to high degree of the CPP mode confinement, relatively low propagation and bending losses, and single mode operation achievable for the CPP [14–18]. The inverse geometry, namely, a triangular metal wedge supports a plasmon-polariton mode (*wedge plasmon-polariton*, WPP) that is, in a way, complementary to the CPP mode. Edge modes were shown to support strongly localized plasmons both theoretically and experimentally [19–22] and it was recently shown that WPPs, while showing significantly smaller modal size than CPPs, exhibit similar propagation length as CPPs [21]. At telecom wavelengths (wavelength bands around 1.31 and 1.55 μm), WPP guiding properties were found to be superior to the ones offered by CPPs, where low losses for CPPs are achievable for relatively large mode sizes [23].

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First experimentally investigated structures were fabricated using the *focused ion beam* (FIB) technique. In the perspective of future applications, the FIB-based approach has certain limitations due to high cost, complexity and low throughput. In addition, FIB-fabricated components are hard to interface with optical fibers to achieve efficient end-fire excitation. Thus, experimental realization of components that are robust, simple to fabricate and easy to interface with outside world is of great interest for future investigations of subwavelength plasmon guiding as well as for development of functional plasmonic devices.

Large-scale fabrication of profiled metal surfaces remains a challenging task. While sharp grooves and wedges can easily be made in silicon using standard lithographic and etching techniques, profiling metal surfaces often requires complex fabrication techniques like FIB [17, 18, 20]. Here, we describe wafer-scale fabrication methods that allows replicating a profiled silicon surface in metal. The fabrication approach is based on standard planar cleanroom processes and allows integration of plasmonic structures with lab-on-a-chip devices.

2.1 Making metal V-grooves

A large-scale method for the fabrication of V-groove plasmonic waveguides is based on the nanoimprint lithography process [35]. A schematic of the fabrication method is presented in Fig. 2. The developed process where V-grooves are first

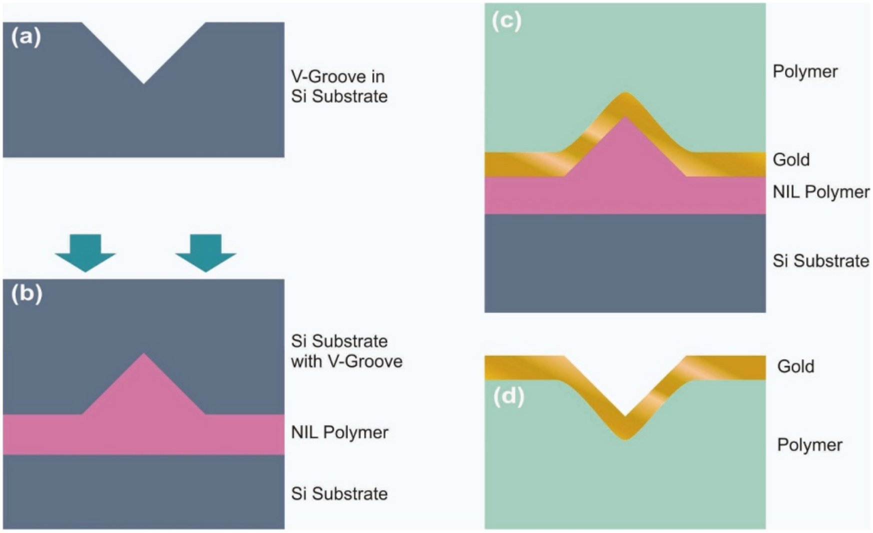

Fig. 2 Schematic of the fabrication steps: (**a**) V-grooves are made in a silicon stamp, (**b**) the silicon stamp is imprinted into a nanoimprint polymer layer (PMMA) on a silicon carrier wafer, (**c**) a negative copy of the stamp is covered with a layer of gold and then UV curable polymer (Ormocomp), (**d**) PMMA layer is dissolved releasing the V-groove structure.

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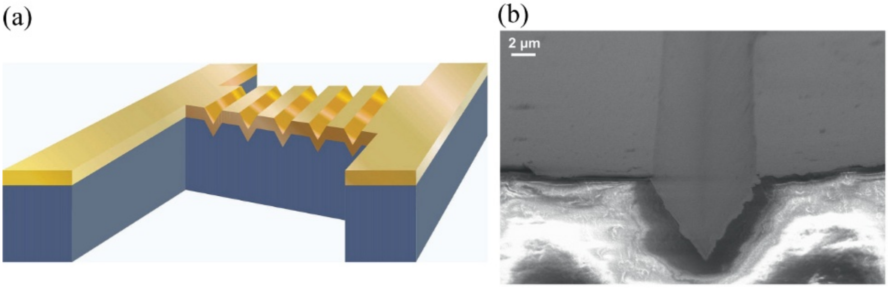

Fig. 3 (**a**) Schematic of the fabricated sample with V-grooved waveguides (gold on polymer substrate) having easy fiber-access configuration (not in scale) together with (**b**) the scanning electron microscope (SEM) image of the fabricated V-groove, 200-nm-gold layer on top of a transparent polymer (the polymer is charging during SEM investigation). The gold edge is ragged due to breaks from ultrasound agitation.

made in a silicon substrate and then replicated in metal using nanoimprint process allows reducing the roughness of the metal film on the sidewalls of the groove. This is achieved by using the backside of the deposited film, similar to the process of template-stripping [36]. The main idea of the method is to make a metal replica of a profiled silicon structure where any desired geometry can be obtained via standard patterning and etching techniques. This approach is used to transfer structures from a silicon stamp to a PMMA (polymethyl methacrylate polymer) layer. After the imprint process, gold is deposited on the PMMA, followed by deposition and selective UV exposure of a hybrid polymer (Ormocomp). Once the Ormocomp layer has been post exposure baked, the PMMA layer can be dissolved, leaving a gold-on-polymer replica of the initial silicon stamp (Fig. 3). In this approach, the quality of the gold surface is expected to be better than that achieved with standard deposition techniques [35, 37].

The method described here should be viewed as a general template for replicating silicon structures in gold on polymer, and can be readily changed to different geometries. Profiling of silicon stamps can be achieved by using a variety of established techniques including reactive ion etching (RIE) (both isotropic and anisotropic) and wet etching using KOH. For example, samples fabricated via wet etch of silicon have limitations of an apex angle fixed to 70° and easy patterning of only straight waveguides [35]. In this case, thermal oxidization of silicon structures can be used to alter the groove geometry, providing different apex angles, for example, decreasing the angle from 70° to 50° [35]. In order to make waveguides of different geometries (bends, couplers) wet etch of silicon can be replaced by RIE where nearly any desired channel geometry is achievable. Since RIE is a complex process, better reproducibility and homogeneity across the wafer can be achieved via combination of RIE with oxidization process that helps to change the geometry and smoothen out the surface (Fig. 4).

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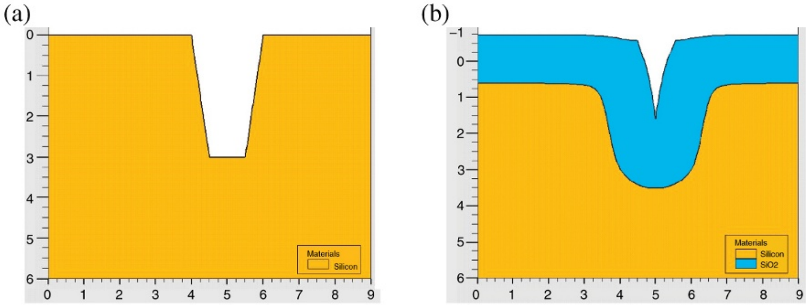

Fig. 4 Simulation of thermal oxidization on (**a**) a reactive ion etched channel with sloped sidewalls and flat bottom: an oxidization step can transform this geometry into (**b**) smooth high angle V-grooves (2D process simulator from Silvaco, SSuprem4). Scales are in micrometers.

The results of optical characterization of the fabricated V-groove waveguides using scanning near field microscopy (SNOM), showing broadband transmission with subwavelength confinement and propagation lengths exceeding one hundred microns are reported elsewhere [37].

2.2 *Making metal wedges*

For fabricating triangular metal wedge waveguides a wafer-scale, parallel method based on standard UV lithography is developed. The developed fabrication procedure provides waveguides that are compatible with fiber optics giving the possibility of easy in- and out coupling. Such geometry can not be achieved by standard deposition techniques since depositing a metal layer on a sharp tip (for example, in silicon) would result in smoothening of the edge. A standard fabrication sequence of lithographic and etching steps to achieve a wedge in a substrate combined with standard metal deposition can therefore only be used for making rounded-top or trapezium-shaped wedges [38]. The fabrication steps of the developed procedure are shown schematically in Fig. 5. First, V-grooves are etched in silicon via standard KOH-etch process, and 500 nm of gold is e-beam evaporated on the silicon wafer with etched V-grooves.

The described procedure provides straight wedges with the fixed apex angle of 70.5° (due to wet etch of silicon). The apex angle of the V-groove made in a substrate can be changed via an oxidation process [35]. Experimental observations of plasmon-polariton low-loss guiding at telecom wavelengths (propagation length ~120 μm) by triangular metal wedges made by the described technique are reported in [22].

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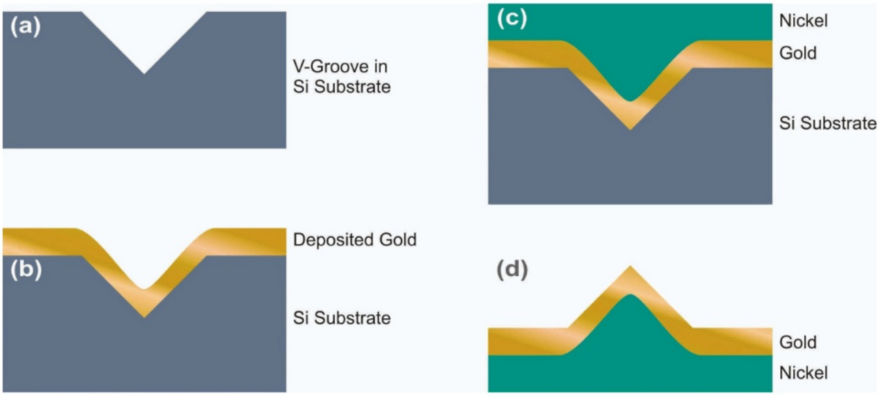

Fig. 5 Schematic of the fabrication steps: (**a**) V-grooves are etched in a silicon substrate using wet etch, (**b**) gold is deposited (note smoothening of the V-groove bottom after the deposition), (**c**) nickel is deposited, (**d**) silicon substrate is dissolved leaving the wedges in gold.

Using electroplating deposition, 53-μm-thick layer of nickel is then deposited on top of the gold-covered wafer. Removal of silicon substrate completes the fabrication sequence yielding straight wedges of gold (Fig. 6).

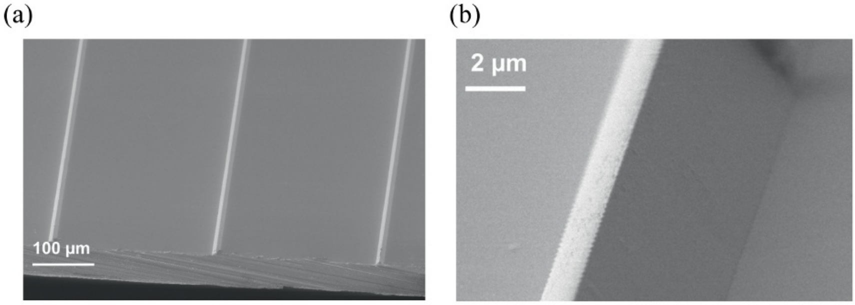

Fig. 6 (**a**) SEM image of the fabricated wedge gold waveguides together with (**b**) a close-up of the fabricated wedge (wavy edge at the lower end is due to charging effects). Marks and facet defects are due to rough sawing of the metal.

Metal wedges can also be produced via a nanoimprint lithography process similar to the fabrication technique used for making V-grooves (Fig. 2). In this case, sharp wedges are first made in silicon and then replicated in metal. By successive reactive ion etching and oxidation processing steps, different-shape silicon wedges can be fabricated [39, 40]. Figure 7 shows an example of a silicon wedge made via RIE, oxidization and the oxide etch processes.

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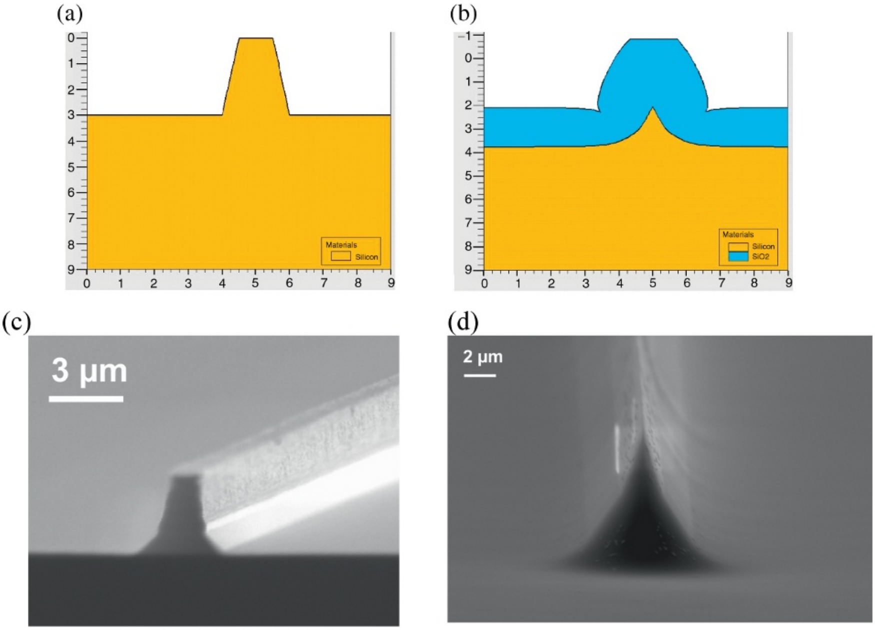

Fig. 7 Simulation of thermal oxidization on (**a**) a reactive ion etched silicon wedge where (**b**) oxide (blue) can be removed subsequently in a highly selective etch (buffer hydrofluoric), leaving sharp wedge (scales are in micrometers) together with SEM images of the fabricated silicon wedge (**c**) after RIE and (**d**) after oxidation and subsequent oxide removal.

3 Fabricating Plasmonic Nanoantennae

Nanoantenna fabrication requires a procedure that combines high reproducibility, robustness and ability of creating small interparticle gaps. Here, we report on nanoantennae fabrication method based on electron beam lithography that offers controllable way of manufacturing high density plasmonic substrates for example, for surface enhanced Raman scattering. Using EBL nanoantenna arrays made of paired elliptical gold particles for particle sizes down to several tens of nm and gaps between particles down to 15 nm can be fabricated (Fig. 8).

In this approach, the arrays are first patterned on an EBL resist and then created either on a substrate or inside the etched holes via metal deposition and lift-off

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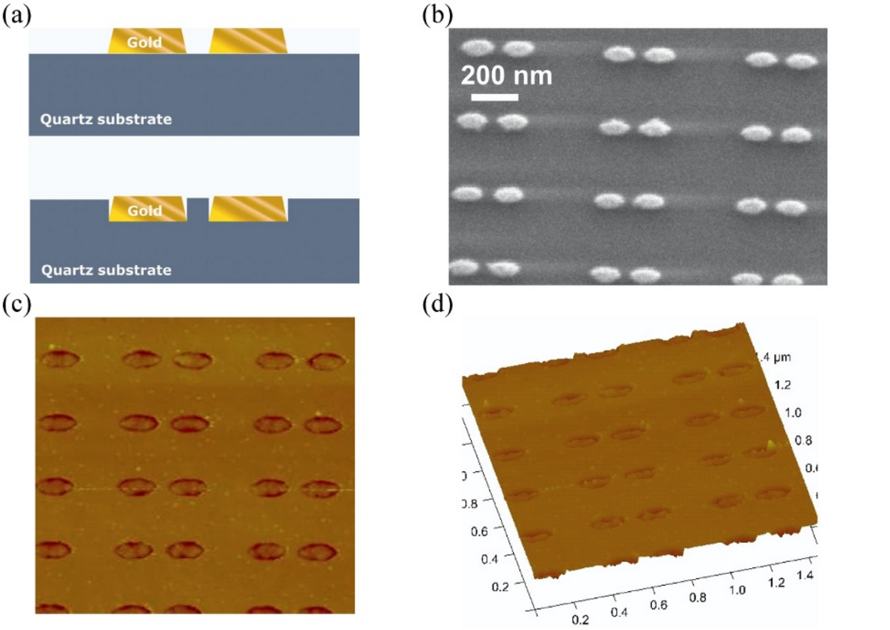

Fig. 8 (**a**) Schematic of the paired gold particles on top of or embedded into a quartz substrate together with (**b**) SEM image of the antenna array on top of a quartz substrate and (**c, d**) atomic force microscope (AFM) images of the embedded antenna array (AFM scale is in micrometers).

process. Detailed samples' description together with the transmittance and reflectance spectra in the visible range exhibiting strong resonances for the polarization, where the electric field is parallel to the major axis of the elliptical particle, are reported in [41].

For optical nanoantennae, two fabrication issues are of great importance, namely, reproducibility of particle sizes and especially interparticle gaps and surface roughness. For gold particles on quartz, the surface roughness is quite low (around 1 nm RMS) [41]. However, structures with gold particles created inside the etched holes have increased roughness due to an additional step of RIE. Moreover, creating a flat surface with embedded metal particles is a challenging task requiring careful optimization of both etching and deposition processes. A possible way of making flat nanoantennae structures is based on a 'flip' process. In this approach, the gold structures are first fabricated on a smooth substrate surface (quartz) and then covered with a curable polymer (like Ormocomp) followed by the substrate removal (Fig. 9).

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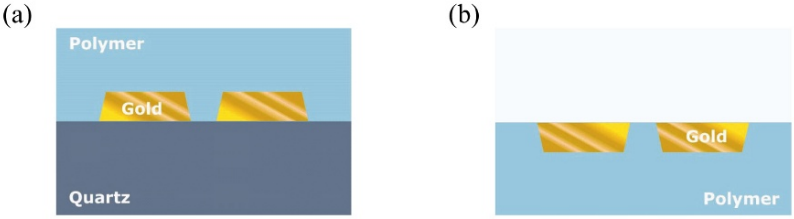

Fig. 9 Schematic for making low-roughness flat nanoantennae array: (**a**) gold particles are patterned on a quartz substrate via electron beam lithography, metal deposition and lift-off and covered with a curable polymer followed by (**b**) substrate removal.

In contrast to chemical methods that always have a dispersion of particle sizes, EBL offer a highly controllable way of producing nanoparticles of the same size and interparticle gaps. However, making interparticle gaps below 10 nm becomes increasingly difficult. This calls for new methods that could combine controllable planar methods as lithography and chemical approaches of creating reproducible interparticle gaps [42]. Thus, a large-scale technique for creating nanoantennae requires novel assembly methods, for example, where chemically created dimers are assembled on a prepatterned or functionalized surface.

4 Conclusion

Development of robust large-scale fabrication techniques based on standard parallel processes is a requisite for further progress in application-oriented or 'practical' plasmonics. In the area of subwavelength plasmon-polariton guiding along metal grooves or wedges, nanoimprint-based technique of producing plasmonic waveguides that are compatible with fiber optics opens up the possibility of developing components for 'real-life' applications ranging from integrated optics to biosensors. The method based on combined nanoimprint and standard photolithography is highly adaptable to different designs and is compatible with lab-on-chip technology that is important for future bio-technology applications. Along with the development of large-scale nanofabrication techniques, improving and perfecting the structural quality of plasmonic structures is the key step towards plasmonic applications. Besides conventional methods of decreasing surface roughness of deposited metal films like optimization of the electron beam deposition process [43], employing new fabrication techniques based on replica or 'flip' processes offers simultaneous substrate planarization that allow reducing the surface roughness of the metal structures and thus creating plasmonic components with improved performance.

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