Gold Stripe Optical Waveguides Fabricated by a Novel Double-Layered Liftoff Process

Jin Tae Kim, Suntak Park, Seung Koo Park, Min-su Kim, Myung-Hyun Lee, and Jung Jin Ju

To fabricate uniform and reliable thin gold stripes that provide low-loss optical waveguides, we developed a novel liftoff process placing an additional SiN_x layer under conventional photoresists. By patterning a photoresist and over-etching the SiN_x, the photoresist patterns become free-standing structures on a lower-cladding. This leads to uniform metal stripes with good reproducibility and effectively removes parasitic structures on the edge of the metal stripe in the image reversal photolithography process. By applying the newly developed process to polymer-based gold stripe waveguide fabrication, we improved the propagation losses about two times compared with that incurred by the conventional image-reversal process.

Keywords: Surface plasmons, polaritons, metal stripe, polymer waveguide.

I. Introduction

Thin metal stripes embedded in a dielectric material have attracted a great deal of attention in integrated optics because they have the ability to transmit light into the physical dimension of the diffraction limit of lights with satisfactory propagation loss [1]. Optical polymers as cladding materials have low propagation loss and provide cost-effective fabrication processes. Thus, polymer-based metal stripe optical waveguides and their applications in integrated devices, such as optical attenuators [2], [3], couplers [4], [5], modulators [6], and Bragg gratings [7], [8], have been widely studied. Another emerging field is optical interconnection where a high-speed serial interface between chips has been demonstrated with metal stripes embedded in a polymer cladding [9]-[11].

The guidance of the light wave along a thin metal stripe is explained by surface plasmon polaritons (SPPs), which are quasi-two-dimensional electromagnetic waves propagated along a metal-dielectric interface. The continuous scaling down of the thickness of metal films embedded in a homogenous dielectric material makes the SPP modes become low-loss waveguides, so-called long-range surface plasmon polaritons (LRSPPs) with propagation distances in excess of several centimeters [12]. In addition, the field distribution of the LRSPP mode can be adjusted to that of single-mode fiber by varying the metal thickness and width.

Since the SPP mode is tightly confined to the metal surface, the propagation loss is very sensitive to the surface condition of the metal stripe. When we fabricate the metal stripes by photolithography, improper liftoff in the image reversal patterning processes by using conventional single-layered photoresist may generate sharp pin-like and shark-fin-like structures on the edges of the metal stripes [13]. These structures

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increase the propagation loss. This is a disadvantage and an obstacle to LRSPP waveguide applications. Therefore, development of new fabrication methods which provide proper square cross sections of the metal lines without parasitic structures is highly required.

In this paper, we present a novel image reversal photolithography process to fabricate low-loss gold LRSPP waveguides by using a double-layered liftoff process. The liftoff process produces an overhanging structure of the patterns that is defined under the developed photoresist layer, resulting in well developed photoresist patterns from the lower-cladding. By separating the photoresist patterns with the lower cladding, we effectively removed unnecessary structures and obtained gold stripes with nearly perfect square cross sections. To evaluate the waveguide properties of the gold stripe optical waveguides, we fabricated them by the proposed liftoff process, and the propagation loss properties of the fabricated waveguides were compared with those of the gold waveguides fabricated by the conventional image reversal process.

II. Concept of Double-Layered Liftoff Process

Polymer-based metal stripe optical waveguides are fabricated by three simple steps: formation of a lower-cladding layer, thermal evaporation of the metal, and formation of an upper-cladding layer. Of many methods to form a metal stripe, a liftoff process is the most cost-effective because the unnecessary part of the evaporated metal film can be easily removed by wet-etching of the photoresist. However, imperfect formation of overhanging structures in the developed photoresist results in the generation of sharp pin-like and shark-fin-like structures on the edges of the metal stripe [13].

To prevent the formation of those parasitic microstructures on the metal stripes, we developed a novel liftoff process using double layers of photoresist and SiN_x as shown in Fig. 1. Instead of directly forming the photoresist on the lower-cladding layer, a 50 nm thick SiN_x layer was formed on the polymer cladding layer by chemical vapor deposition. Then, the photoresist, AZ520E from Clariant Inc., was coated on the SiN_x layer (Fig. 1(a)). The photoresist was patterned by UV exposure and then developed (Fig. 1(b)). The SiN_x was then etched in a buffered oxide etchant (BOE) to form an overhanging structure (Fig. 1(c)), and a metal film was deposited by thermal evaporation (Fig. 1(d)). Then, the photoresist and SiN_x layers were removed by an AZ 340 developer and BOE, respectively, (Figs. 1(e) and (f)). Finally, the upper-cladding layer was formed (Fig. 1(g)).

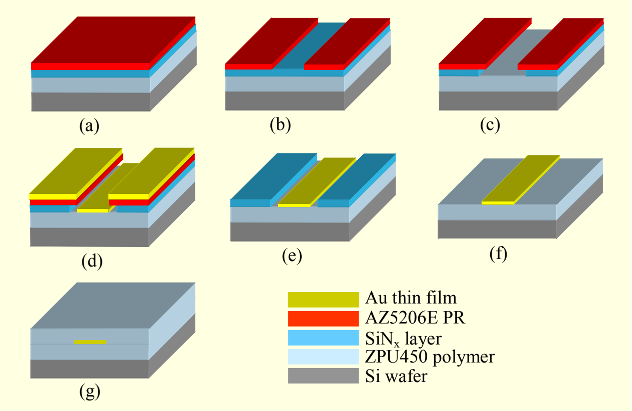


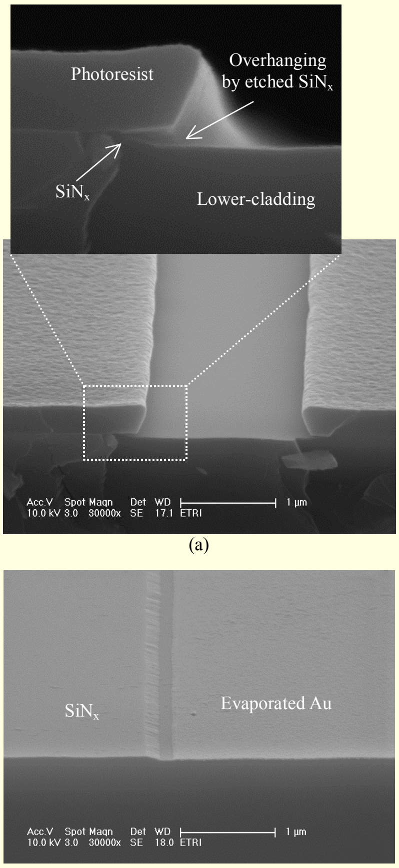
Fig. 1. Schematic showing the proposed double-layered liftoff process to fabricate the metal stripe optical waveguide [14].

The developed double-layered liftoff process has three advantages for the formation of metal stripe patterns on polymer layers. First, it prevents the disappearance of an overhanging structure in photoresist caused by unstable contact conditions between the photoresist and photo-mask. Unstable contact is attributed to the so-called edge bead near the edge of the spin-coated polymer layer. In the proposed double-layered liftoff process, however, the overhanging structure could be formed without dependence on the photoresist patterns; the overhanging structure is formed uniformly. Second, the patterning of the SiN_x layer protects the polymer surface from roughening. This is because the SiN_x layer does not interact with the polymer cladding layer and is perfectly removed by BOE wet etching. Consequently, the surface roughness of the evaporated metal film is the same as that of the polymer surface. Finally, the SiN_x layer protects the polymer surface from damage caused by a photoresist remover during the liftoff step. Thus, the adhesion between the undercladding and upper-cladding layers increases.

A dual photoresist process is suitable to fabricate metal stripes on a polymer surface. However, this process is not satisfactory for patterning metal stripes on a polymer surface because the photoresist slightly interacts with the polymer layer. For perfect removal of the residual photoresist on the polymer surface, a reactive ion etching (RIE) process is performed after development of the photoresist. There is no stop layer on the polymer surface. Therefore, the surface roughness of the polymer layer may increase and the surface roughness of the evaporated metal also increases. If the RIE process is not used, the residual photoresist may degrade the surface quality of the evaporated metal film.

III. Experiment and Results

To evaluate the efficiency of the proposed liftoff process, gold stripe optical waveguides were fabricated by using the process, and the optical properties of the fabricated waveguides



(a)

(b)

Fig. 2. SEM images taken after each double-layered liftoff process step was performed: (a) after the photoresist and the SiN$_x$ were developed, and (b) after the gold film was evaporated and the photoresist was removed.

were compared with those of a waveguide which was fabricated by a conventional liftoff process using only photoresist.

The cladding polymer material is a UV-curable fluorinated resin based on acrylate supplied by ChemOptics Inc., trademarked ZPU13-450, which has a low refractive index of 1.451 and a material loss of 0.1 dB/cm at a wavelength of 1.3 µm [15]. The thickness of the lower- and upper-cladding was 30 µm. The gold evaporation process was performed at a relatively low evaporation rate of 0.02 nm/s. We formed two gold films with thicknesses of 10 nm and 12 nm, respectively. For improvement of stability and perfect curing of the polymer film, all of the waveguides underwent a thermal curing process in a nitrogen oven at 160°C for 60 minutes.

Figure 2 shows SEM images taken after the proposed double-layered liftoff process was performed. Figure 2(a) shows the overhanging structure formed under the photoresist after the SiN$_x$ was etched in a BOE. The overhanging of the photoresist could be enough to prevent the gold stripe from generating parasitic microstructures on the edge of the stripe. However the overhanging may disappear at the edge of the polymer cladding. The evaporated metal film may adhere to the sidewall of the photoresist and, as a result, a uniform metal stripe without parasitic nanostructures is impossible. On the other hand, 50 nm thick overhanging structures formed under the photoresist separate the photoresist from the lower-cladding surface as shown in Fig. 2(a). Therefore, the evaporated metal which is adhered to the side wall of the photoresist is not connected to the metal stripe. As a result, it is expected that a metal stripe with a clear square cross section is fabricated after the removal of the photoresist and the SiN$_x$ layer.

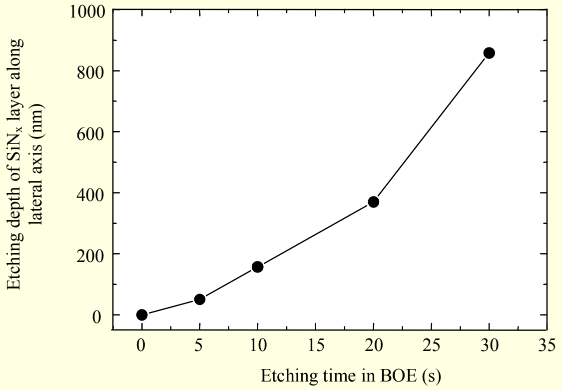


Fig. 3. SiN$_x$ etching rate with BOE (1:6).

Figure 2(b) shows a SEM image taken after removal of the photoresist followed evaporation of the gold film. Clear separation of the metal stripe from the SiN$_x$ layer is clearly displayed. As a result, parasitic structures such as sharp pin-like and shark-fin-like structures were not generated and a nearly perfect gold stripe with a clear square cross section was fabricated.

Over-etching of the SiN$_x$ layer along the lateral direction allows the photoresist on it to come into contact with the undercladding polymer surface. Thus, the overhanging structure disappears and low-quality metal stripes may be fabricated. To prevent this, optimization of the SiN$_x$ etching time is necessary. Figure 3 shows SiN$_x$ etching rates in relation to the etching time in BOE, where 1:6 BOE was used. The etching depth in the lateral direction was estimated from the length of the overhanging structure under the photoresist. The SiN$_x$ etching rate in the lateral direction increases exponentially as the etching time increases. From the experimental results, we chose 10 seconds etching time to form a 200 nm deep overhanging structure.

Figure 4 shows AFM images of a fabricated gold stripe on a polymer cladding. Figure 4(a) shows a stripe fabricated by a single photoresist. The sharp pin-like and shark-fin-like structures on the edge of the stripe are shown. On the contrary,

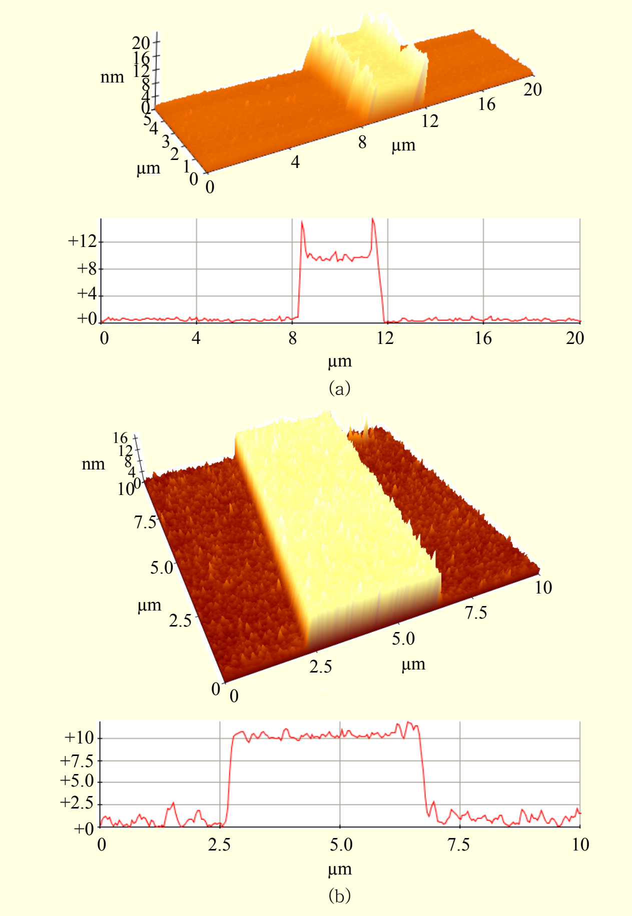


Fig. 4. AFM images of the evaporated gold stripe on the polymer undercladding: (a) fabricated by a conventional liftoff process and (b) fabricated by the proposed double-layered liftoff process.

in the stripe fabricated by using the proposed double-layered liftoff process, those parasitic microstructures disappeared and a smooth sidewall profile and a nearly perfect square cross-section were exhibited as shown in Fig. 4(b). A surface roughness of less than 1 nm was obtained.

To evaluate the effect of the new liftoff process on the gold LRSPP waveguide, we measured the optical properties of the fabricated gold stripe optical waveguides. To compare, the same waveguides were fabricated by the conventional liftoff process using a single photoresist. Metal stripe widths in the range from 2.0 µm to 5.5 µm (with a 0.5 µm step) were fabricated. The fabricated samples were cut into desired lengths (1.5 cm, 2 cm, and 2.5 cm) to measure the optical propagation loss with a standard cutback method. The propagation was measured by a cutback method using polarization maintaining fiber at a wavelength of 1.3 µm. The TM-polarized light from a polarizer was coupled into the waveguide input via butt-coupling to excite the SPP mode. The waveguide output powers were coupled into the fiber, and then the transmitted powers were measured with an optical power meter. An index-matching liquid was used to ensure reliable optical coupling.

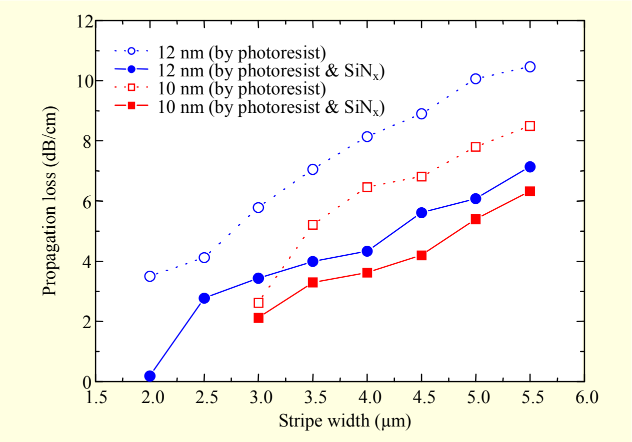


Fig. 5. Propagation loss of the gold stripe optical waveguides as a function of width.

Figure 5 shows the dependence of waveguide loss on width of the gold stripe. As in previous studies, the propagation loss decreases as the stripe width narrows for the two waveguides. For the gold stripe optical waveguide fabricated by the newly developed liftoff process, the propagation loss is smaller than those of the waveguides fabricated by a single photoresist. A 12 nm thick gold LRSPP waveguide fabricated by the double-layer process has lower propagation loss than the 10 nm-thick gold LRSPP waveguide. Those results are attributed to the disappearance of the parasitic structures on the stripe edge as shown in Fig. 4(b). The propagation loss of the polymer-based LRSPP waveguide could be caused by many factors, such as ohmic loss of the metal, absorption loss of the cladding material, and non-uniformity of the refractive index of the cladding. Of these factors, the inhomogeneous metal structure generated by the unstable conditions in the fabrication procedure acts as a major loss-generating factor because the SPP mode is very sensitive to the surface condition of the metal. By preventing the generation of parasitic structures on the gold stripes with the double-layered liftoff process, formation of homogeneous metal geometry is enforced. Consequently, the propagation loss of the polymer-based LRSPP was improved. The coupling losses of the two waveguides are the same because the two gold LRSPP waveguides have the same thickness and width.

VI. Conclusion

With the aid of a novel double-layered liftoff process using photoresist and an SiN$_x$ layer, we fabricated good quality gold stripes embedded in a polymer-cladding. They transmit a light wave with lower propagation loss compared with those of the waveguides fabricated by the conventional image-reversal process. An overhanging structure under the photoresist was made by wet etching of the SiN_x layer, which made the developed photoresist free-standing. By applying the free-standing photoresist patterns in the fabrication of gold stripes fabricated by an image reversal process, unnecessary parasitic structures on the edge of the gold stripe patterns were effectively removed, and uniform metal stripe patterns were formed, which resulted in improved propagation characteristics of the gold stripe optical waveguides. From the experimental results, we confirmed that the newly developed double-layered liftoff process is an efficient and reliable fabrication method for metal waveguides with low propagation loss.

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