Coupling of plasmon waveguide modes to free-space optics through surface sculpting of ultrathin freestanding films

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Abstract **— A method for coupling between nanomembrane-based optical waveguides utilizing long-range surface plasmon polaritons and propagating free-space modes is described and analyzed. We base our approach on three-dimensional surface sculpting of freestanding ultrathin metal or metal-composite membranes utilizing bulk micromachining of their sacrificial support. The approach ensures a less stringent alignment conditions compared to some alternative methods. We fabricated the experimental samples of the coupling structures utilizing a combination of thin film deposition technique and bulk micromachining for 3D sculpting of sacrificial silicon substrate.**

Keywords **— Integrated Optics, Nanomembranes, Nanophotonics, Plasmonic Devices, Polaritons, Optical Waveguides, Surface Plasmons.**

I. Introduction

RECENTLY a novel family of passive waveguide-based components for broadband optical communications was introduced, the devices utilizing the propagation of surface plasmon-polaritons on metal-dielectric interface [1]. These typically use either thin metal strips immersed in dielectric or a dielectric sandwitched between two metal strips. To ensure minimum losses, these waveguides are usually utilizing long-range surface plasmons polaritons (LR SPP) in fully symmetric structures [2, 3].

Surface plasmons polaritons are confined to the metal-dielectric interface and are evanescent in perpendicular direction. The wavevector of SPP is always larger than the wavevector in free space and at optical frequencies the wavelengths of the SPP are very small, even reaching nanometric lengths [4, 5]. This means that the SPP wave-guides are very convenient for miniaturization and the fabrication of ultracompact photonic circuitry. Another important advantage is the possibility to use the identical waveguide simultaneously for guiding light and for guiding the controlling electrical signals [2]. Also, the SPP components generally have high field localizations, thus enabling the use of nonlinear photonic materials, ensuring the possibility to incorporate active components [6].

An important issue in SPP guides is their coupling with propagating waves. Since their wavevector is much larger than that in free space, it is necessary to impart to the wave the missing momentum in order to enable coupling. There are various schemes to ensure this, Fig. 1.

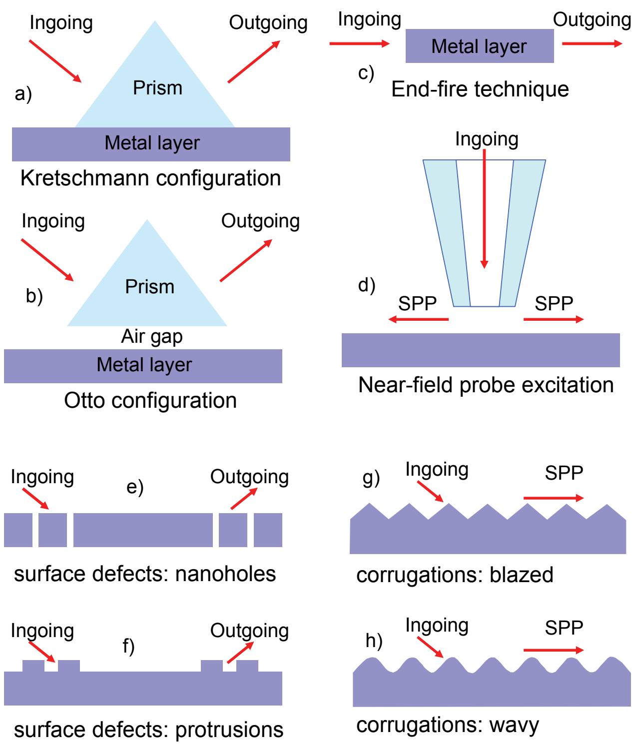

Fig. 1. Some configurations for coupling between free-space and SPP modes: prism couplers in a) Kretschmann and b) Otto configuration; c) end-fire coupling; d) near-field probe excitation; coupling through surface defects which may consist of e) nanohole arrays or f) surface protrusions; surface corrugations: g) blazed or h) wavy.

The oldest methods include prism couplers in either Kretschmann [7] or Otto [8] configuration which utilize attenuated total reflection. Another may to excite the SPP is to use near-field optical probe [9]. A large group of coupling methods are topological surface defects [10] like subwavelength apertures or surface protrusions, e.g. various pillars, bumps, etc. Finally, a group of coupling structures includes various types of surface corrugations [11-12].

In coupling it is important to ensure that the maximum

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percentage of the incoming free-space mode is converted to SPP (and vice versa for the output). At the same time, it is important to ensure the smallest leakage and scattering losses.

Recently a novel type of building blocks for plasmonic devices was introduced, the freestanding ultrathin membranes (nanomembranes) [13-15]. A nanomembrane guide is a freestanding metal or metal-composite homogeneous or laminar structure with an overall thickness of about 10 nm, and with lateral dimensions up to a cm [13, 16, 17]. These structures ensure a full symmetry for LR SPP and thus minimum losses [18]. In addition to that they offer the maximum refractive index difference between the medium and the guide.

It is convenient if these structures are coupled to propagating modes without a direct physical contact with the nanomembrane. A way to excite them is to use end-fire method [19, 20], however this requires a careful fiber-waveguide alignment.

In this paper we introduce and analyze a novel coupling method for LR SPP optical waveguides based on nanomembranes. The method uses direct surface sculpting and is applicable without a special alignment procedure. We present its theoretical foundations and outline experimental methods. Further we give some experimental results and draw some conclusions.

II. Theory

Our basic waveguide configuration is shown in Fig. 2. The SPP propagate along the x direction and are evanescent along the z axis. The lateral dimensions (along the x and y-axis) are of the order of tens of millimeters. The substrate and the superstrate are described by an identical relative dielectric permitivity ε_1 and the structure is fully symmetrical.

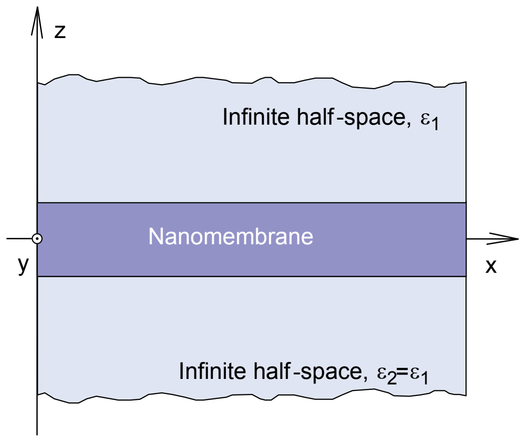

Fig. 2. Basic configuration of a guide for surface plasmon polariton propagation (metal-dielectric interface)

The structure is very simple, and its microfabrication procedure straightforward [14]. The freestanding nanomembrane is supported at its edges by a silicon rim.

The coupling structures are incorporated into the freestanding nanomembrane itself. Its large lateral dimensions allow for ample space both at the waveguide input and the output.

The basic approach to nanomembrane sculpting is illustrated in Fig. 3. 3D surface patterns are fabricated at the waveguide input and output. The intrinsic stretching of the membrane between the two couplers ensure minimum scattering losses and leakage in between.

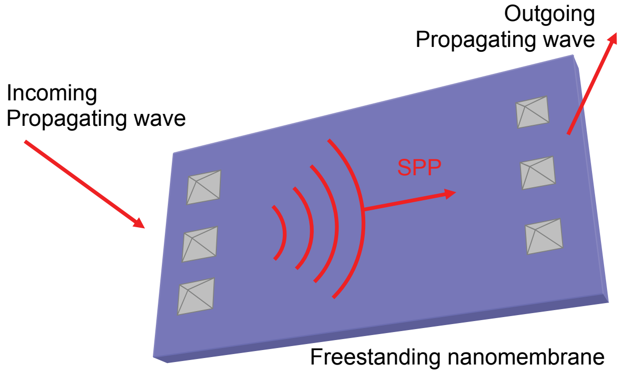

Fig. 3. Propagating wave to surface plasmon couplers using surface sculpting

A cross section of the sculpted nanomembrane is shown in Fig. 4. The sculpted couplers are shown in their two generic shapes, as pyramids or hemispheres. Both families of patterns are readily fabricated by the sacrificial substrate micromachining, as shown in the further text. Besides the full pyramids and hemispheres, also truncated pyramids, ellipsoids as well as some other volume shapes are available. The shapes may range from sparse population with a regular pattern (creating in effect a diffractive grating) to a full surface corrugations. It may be said that all coupling methods presented in Fig. 1 e-h may be implemented in this manner.

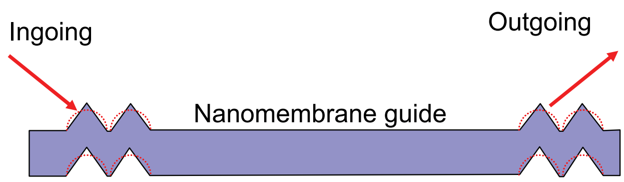

Fig. 4. 3D-sculpted nanomembrane coupling configuration using pyramidal (or, alternatively, hemispherical, shown as dotted red lines) spatial patterns

Fig. 5 shows drawings of two basic surface reliefs for nanomembrane sculpting which may be fabricated using micromachining. The top structure, the one with hemispherical protrusions, can be obtained by isotropic etching of the sacrificial silicon substrate through circular widows in photolithographic mask (or, alternatively, by using some other material for the substrate and utilizing its isotropic etchants. The bottom structure can be obtained by anisotropic etching of silicon with (100) surface orientation through square windows aligned along [110].

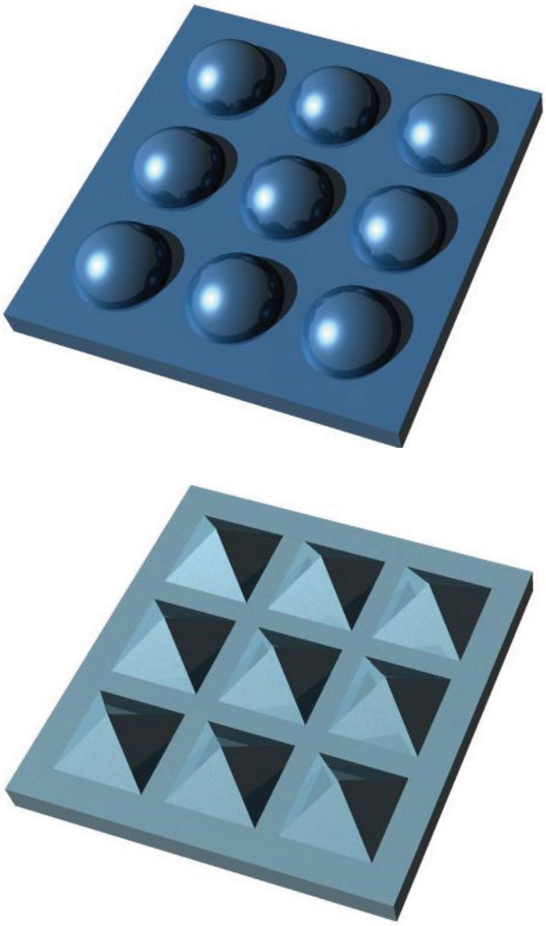

Fig. 5. Drawings of two surface reliefs for nanomembrane sculpting fabricated using micromachining. Top: isotropic etching through circular widows in photolithographic mask; bottom: anisotropic etching of silicon with (100) surface orientation through square windows aligned along [110]

III. Experimental

The procedure for the fabrication of nanomembranes themselves is described in some detail in [14]. In this text we outline the method to sculpt 3D patterns in the nanomembrane surface.

To fabricate our metal-composite nanomembranes we started from single crystal silicon wafers with (100) crystallographic orientation. After the standard preparation procedure we delineated square windows in the photolithographic masks. The squares were aligned along the [110] direction. After that the conventional bulk micromachining was used to fabricate square silicon diaphragms 20-40 μm thick with the etched pyramids in its surface. Each diaphragm had a silicon rim to serve as a support for our structure.

An alternative approach is to use rounded holes (or actually any shape) and isotropic etching.

The next step was to use radiofrequent sputtering to deposit a (5-20) nm thin metal-composite layer onto the silicon diagram. To ensure the desired composition of the deposited layer sputtering was done in oxidizing or nidritizing atmosphere.

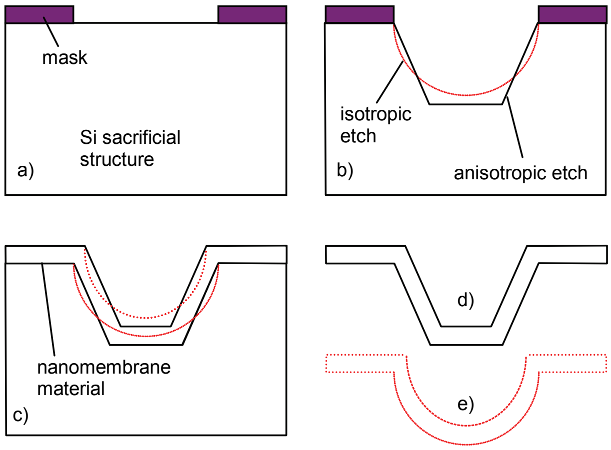

Fig. 6. Technological steps for the surface sculpting of freestanding nanomembranes. a) Si single crystal wafer with spinned-on mask; b) etching; c) mask removal and nanomembrane deposition; d) sculpted structure after anisotropic etch of sacrificial silicon; e) sculpted structure after isotropic etch.

The next step was to use bulk micromachining to completely remove the Si diaphragm which thus served as a sacrificial structure. A very important step in the procedure is releasing the nanomembrane from the etching solution which mus be done very carefully.

After the nanomembrane is fabricated and released it is very robust and actually allows handling with little or no extra precautions. The silicon rim even allows for handling the freestanding nanomembrane by holding the edges with bare fingers. In this manner, although metal-composite nanomembranes belong to nano-objects, they simultaneously belong to macroscopic objects and allow easy manipulation. The maximum nanomembrane areas were up to a few cm^2 and the aspect ratio in excess of 500,000 [13-15].

It is interesting to mention that this procedure can be used to fabricate nanomembranes in a variety of different metals composites. The membranes for LR SPR guides can be made either into planar sheets or narrow strips.

Besides being fabricated as the "naked" metal-composite structures, our nanomembrane can be additionally laminated with nanometer-thick pure metal layers which are deposited on both surfaces (e.g. gold layers), in this way ensuring a wider range of possible materials for the waveguides and still lower losses in the metal part of the guide.

IV. Results

A scanning electron microscope micrograph of the edge of a surface-sculpted pattern on a freestanding metal-composite nanomembrane is shown in Fig. 7. The feature was obviously fabricated by anisotropic bulk micromachining of the sacrificial silicon. In spite of the whole nanomembrane being intrinsically stretched and taut over the silicon rim, the morphology of the coupling structure is well defined.

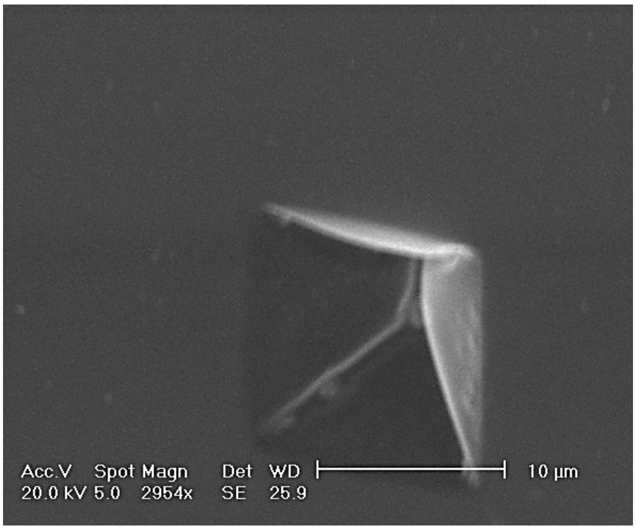

Fig. 7. Scanning electron microscope photo of a 10 μmx10 μm pyramid sculpted on the surface of a metal-composite nanomembrane, thickness 20 nm

The thickness of the nanomembrane was about 20 nm, while the width and length of a single pyramidal surface feature were about 10 μm. It can be seen that the rest of the nanomembrane retains its flatness in nanometric range.

V. CONCLUSION

We report a new approach to propagating-to-SPP mode coupling utilizing 3D surface sculpting by isotropic or anisotropic bulk micromachining of sacrificial silicon support. The structures can be made as two-dimensional arrays, their properties limited by the photolithography procedure applied. The sculpted structures can be used either as DOE-like defect couplers or quasi-continuous surface corrugation couplers. The can be tailored to couple to (and from) propagating modes arriving from a single direction, or (especially if isotropic-etch forms are used) as omnidirectional couplers. There is no need for accurate alignment procedures for coupling with free-space light sources and detectors, nor for any additional elements like prisms or gratings. We believe the tailorability makes the 3D surface-sculpted nanomembranes a valid alternative to other coupling methods for freestanding LR SPP waveguide structures.

ACKNOWLEDGMENT

This work was funded by the Austrian Science Fund (FWF) within the project L521 “Metalcomposite Nanomembranes for Advanced Infrared Photonics” and by the Serbian Ministry of Science and technology within the project 11027 “Microsystem and Nanosystem Technologies and Devices”.

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