Materials Science and Engineering B 149 (2008) 237–241

MATERIALS SCIENCE & ENGINEERING B

www.elsevier.com/locate/mseb

Engineering surface plasmon based fiber-optic sensors

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Received 29 June 2007; received in revised form 7 September 2007; accepted 10 September 2007

Abstract

Ordered arrays of nanoholes with subwavelength diameters, and submicron array periodicity were fabricated on the tips of gold-coated optical fibers using focused ion beam (FIB) milling. This provided a convenient platform for evaluating extraordinary transmission of light through subwavelength apertures and allowed the implementation of nanostructures for surface plasmon engineered sensors. The fabrication procedure was straightforward and implemented on single mode and multimode optical fibers as well as etched and tapered fiber tips. Control of the periodicity and spacing of the nanoholes allowed the wavelength of operation to be tailored. Large changes in optical transmission were observed at the designed wavelengths, depending on the surrounding refractive index, allowing the devices to be used as fiber-optic sensors.

Keywords: Subwavelength apertures; Surface plasmons; Gold films; Optical fibers; Sensors

1. Introduction

There has been substantial interest in the development of surface plasmon engineered structures [1], where the excitation of collective oscillations of electrons by light can be used to make new classes of optoelectronic devices. Especially interesting has been the observation of extraordinary transmission of light through subwavelength apertures [2,3]. Controlling the size and periodicity of an array of subwavelength apertures or by controlling the surface topography of metal around a nano-scale hole one can engineer the structure to transmit light of desired wavelength through the aperture with the efficiency much greater than what would be predicted by diffraction theory. These investigations have been on flat substrates such as glass or sapphire substrates [4,5] or free standing metal films [6]. In this study we focus on using the tips of optical fibers as the experimental platform.

Since the surface plasmon phenomena can be mediated by the refractive index of the surrounding medium, this suggests that these structures can be used as sensors sensitive to the surrounding refractive index. The advantage of studying arrays of subwavelength apertures in free standing metal films is that the refractive index is balanced on either side of the film. In this condition the extraordinary transmission of light is enhanced compared to situations where the refractive index is not matched [7–9]. On flat substrates, depositing a dielectric on subwavelength metallic structures has been used to demonstrate shifts in the wavelength and efficiency of transmitted light [10]. However, free standing metal films are fragile and inconvenient to work with. Flat substrates are robust and easily fabricated, however the very small size of the nanohole structures often leads to difficulties in optical alignment as well issues in base lining the optical spectrum, especially if pinholes or scratches mar the gold surface.

Recently there has been interest in the use of localized surface plasmon resonances for fiber-optic sensing [11,12]. The fabrication of surface plasmon engineered structures on optical fiber tips by focused ion beam (FIB) milling was investigated in this paper and it was shown that these structures are very sensitive to refractive index changes and that the sensors can be designed to operate at designed wavelengths. Using the tips of optical fibers as platforms for investigating surface plasmon engineered structures also turns out to be convenient for a variety of reasons:

(a) Optical alignment is easy and the structures can be easily identified.
(b) Once light is coupled into the fiber the confinement of light to the fiber core is well understood and efficient. Etching of the fiber tip with hydrofluoric acid allows the fiber core to

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doi:10.1016/j.mseb.2007.09.076

be identified. Thus, the subwavelength aperture array can be accurately placed on the core.

(c) Modern focused ion beam milling tools allow generation of arbitrary metallic structures on the nano- to micro-scale with the ability to grayscale the depth of the milling allowing the surface topography of the metal to be controlled in a desired way.

Although this paper is limited in scope to the demonstration of these fiber-optic probes for sensing of refractive index around the fiber tip, the use of the fiber-optic tip as a platform for surface plasmon engineered structures also suggests they could be employed as optical filters or for optical switching applications.

2. Experimental

The fiber-optic tips were prepared by stripping the polymer jacket and then cleaving the fiber with a commercial handheld fiber cleaver to obtain a smooth mirror-like surface. The fiber tips were then inspected and cleaned of particulate if necessary. In the case of fibers with small cores such as single mode optical fibers etching the fiber in a 49% hydrogen fluoride buffered oxide etch (BOE) solution was found to be very useful in determining where to place the nanohole array. Typically the etch was 4–8 min and the fiber tips were then rinsed in deionized water and blown dry with nitrogen. After the etching process, electron beam evaporation of the gold was used to coat the fiber tips. Gold was chosen as the metal since it is highly conductive, can be easily evaporated and is resistant to oxidation. The thickness of the gold films was 180 nm as measured by the quartz crystal monitor. A Hitachi D3100 focused ion beam milling machine with a Gallium ion source, normally used for transmission electron micrograph sample preparation, was used to pattern the gold films on the fiber tips. Typical Gallium ion beam parameters were 40 keV and 0.01 nA at a magnification of 8000 times. The instrument is equipped with software and a beam blanker that accepts a 512 × 512 image file with 8 bit grayscale. This allows the desired pattern to be milled by rastering the ion beam and controlling the duration and beam current appropriately. Optical transmission measurements were performed using a tungsten halogen lamp as the light source, and a 1/4 meter spectrometer, with a 600 line/in. grating, a cooled CCD spectrometer and a multimode optical fiber input. To investigate the effect of changing the refractive index of the medium surrounding the fiber tip, a sensor chamber was fabricated by machining a small metal block that kept the sensor fiber and collecting fiber aligned, while allowing liquids such as water to be applied and removed. Example fabricated structures are shown in Fig. 1. Optimization of the fabrication process lead to the development of nearly uniform holes in the array, as shown in Fig. 1d.

3. Results and discussion

When light is incident on the array of subwavelength apertures where the periodicity is less than the propagation distance of the surface plasmon, conservation of energy and momentum allows one to establish the relationship between the wavevector of the surface plasmon waves k_{sp}, the wavevector of the incident light k_x, and the allowed momentum vectors of the periodic structure P_x and P_y. Bloch's theorem and the periodicity of the structure imply only integer multiples m and n of the momentum vectors are allowed:

$$k_{sp} = k_x \pm m P_x \pm n P_y \qquad (1)$$

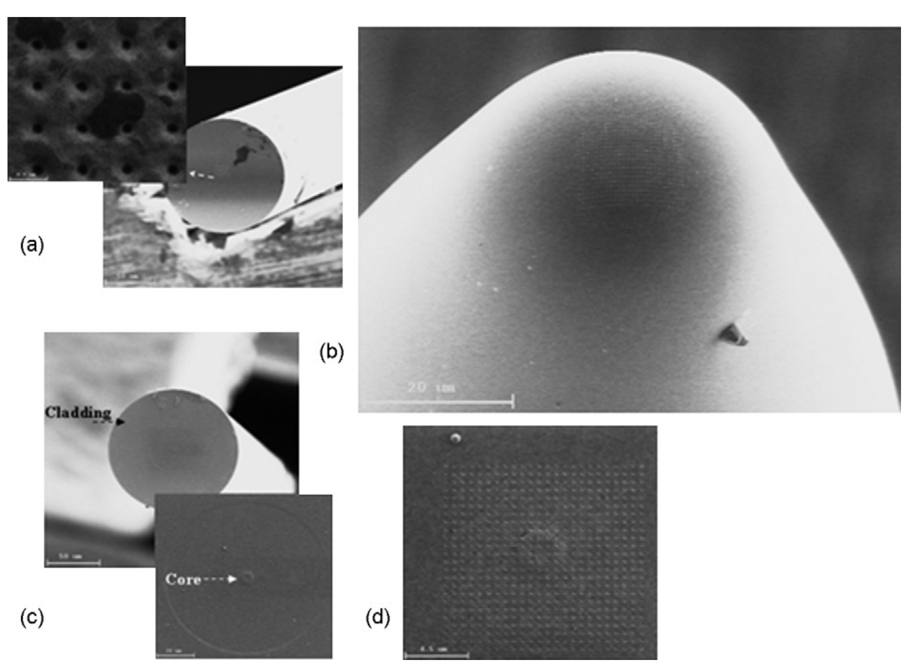

Fig. 1. SEM micrographs showing 24 × 24 nanohole arrays fabricated in 180 nm gold films on: (a) cleaved end-face of a multimode optical fiber and (b) tip of a tapered optical fiber; (c) cleaved end-face of a single mode optical fiber etched with buffered HF and having a 180 nm film of gold; (d) A 24 × 24 nanoholearray on the core region of the fiber tip.