Advanced Metal Nanostructure Design for Surface Plasmon Photonic Bandgap Biosensor Device

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***Abstract*-This paper is intended to demonstrate the effect of coupled surface plasmon polaritons (SPPs) on the optical response of a one-dimensional metal grating nanostructure patterned by electron beam lithography (EBL) on the silicon surface. Variations of the structure parameters allow continuously tuning of these high-transmission bands across the nanostructure plasmon resonance. This phenomenon gives rise to a selective spectral response and a local field enhancement which can be used in the context of nano-optics. We have examined the emission and reflectance spectra through various fabricated structure layers to determine the emissive angle in SPPs modes. The presented results show that the enhanced reflectance through grating nanostructures is important for such a planar design of novel optical biosensor.**

Keywords: surface plasmon polaritons (SPPs), nanostructure, electron beam lithography (EBL), optical biosensor.

I. INTRODUCTION

Advancements in biotechnology have culminated in its integration with semiconductor technologies such as micro-electromechanical systems, resulting in the evolution of biosensors. Biosensors provide applications throughout the process tools for speedy development of drugs and accurate diagnosis and understanding of biological mechanisms [1]. The most widespread label-free detection systems found on the market are based on surface-plasmon resonance (SPR) [2,3]. Biochemical interactions at the sensor surface are monitored by observing the resonant behavior of guided waves at a thin metal film. Today, the market leader is the company BIACORE [4]. Other companies include Applied Biosystems [5] and Texas instruments [6].

In the past decade, the phenomena of surface plasmon resonance (SPR) have been extensively used to investigate optical constants and thickness of thin films, surface properties [7], and molecular interactions on the solid–liquid interface [8-12]. The SPR is a charge-density oscillation that may exist at the interface of two media with dielectric constants of opposite signs, for instance, a metal and a dielectric. This phenomenon was first observed in metal grating in the early 1900s. Kretschmann used a metallic-film-coated (~50 nm) prism to generate a surface plasmon resonance (SPR) signal [13]. Since then, the Kretschmann prism-coupling device has been used extensively to study the optical properties of metallic thin films, including index of refraction (n), extinction coefficient (k), thickness (d), and roughness [14]. For the practical applications of SPR sensing device, we have to apply Frensel equaiton to calculate the total reflectance from a grating structure. Such a periodic metal nanostructures can have very interesting and exciting optical properties which strongly depend on the used materials, layer thickness, and grating pitch. Other than the traditional Kretschmann (attenuated total reflectance (ATR method)) and Otto (frustrated total reflectance (FTR)) configurations, several novel devices based on grating nanostructure of mixed hybrid configuration have been reported in literatures, which include long-range surface plasmon resonance (LRSPR) [15-17] and coupled plasmon waveguide resonance (CPWR) [18].

For our experiments, we prepared one-dimensional patterns of nanostructures by electron beam lithography ELS-7500EX (ELIONIX CO.), the line size is 200nm, the pitch 400nm and 100nm thick resist ZEP520A on silicon substrates. The shape of the individual grating was slightly elongated, exposure area 1.2×1.2mm. In model experiments, a minute change in ambient refraction index resulted in the observable shift of the angle and intensity change in the reflectance. This means that angle shift detection in SPR schemes offers higher sensitivity and miniature system by several orders than the traditional intensity measurements. The purpose of this article is to survey the latest results. They embrace an exhaustive understanding of SPR properties and applications of miniature plasmonic to create (bio)chemical sensors with ultra-high sensitivity and wide dynamic range.

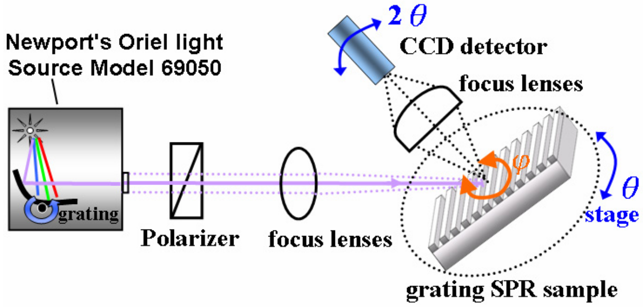


Fig. 1. The reflectivity measurement system for Grating experiment.

Ⅱ. MATERIALS AND METHODS

A. Reflection gratings Principle:

A reflection grating is formed by a periodically symmetrical lamellar reflecting surface. An incident single-frequency plane wave is separated, upon reflection, into different orders. The angles depend on the wavelength of the incident wave. We develop a construction for the angles of the reflected waves produced by a reflection grating. The reflected waves are composed of an infinite sum of plane waves propagating at different angles with respect to the z axis. Fig. 2 shows the construction for the ***k*** vectors of the plane waves [19].

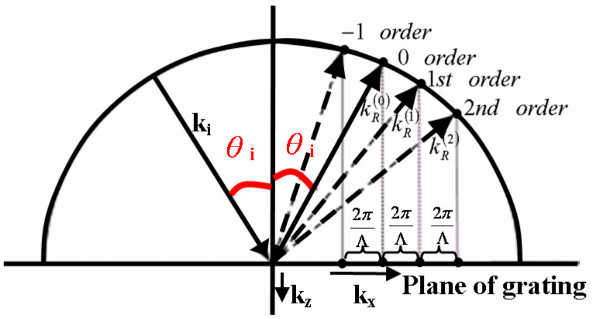


Fig. 2. Construction of angles for higher-order reflections from grating.

The angle of reflection of *m*th order may be related to the angle of incidence, we find from Eq. (1).

$$\sin\theta_R^{(m)} = \sin\theta_i + \frac{m\lambda}{\Lambda} \tag{1}$$

θ_i is angle of incidence, $\theta_R^{(m)}$ is angle of reflection of *m*th order and depends on wavelength, when Λ too large the $\theta_R^{(m)} = \theta_i$ or Λ too small the $\theta_R^{(m)}$ becomes imaginary, therefore k_x becomes surface evanescent wave in x axis propagation.

B. principle of Surface plasmon resonance on grating:

The charge density wave is associated with an electromagnetic wave, the field vector of which reaches their maxima at the interface and decay evanescently into both media. This surface plasmon wave (SPW) is a TM-polarized wave (magnetic vector is perpendicular to the direction of propagation of the SPW and parallel to the plane of interface).

The *grating coupler* is based on light diffraction on a periodically modulated surface of a diffraction grating, the coupling condition may be expressed as Eq. (2)(3), the *Λ* is denotes the pitch of the grating. The SPR dispersion relationship curve for grating coupler is show in Fig. 3. [13,21,24].

$$n_a \sin(\theta) \pm m\frac{\lambda}{\Lambda} = \pm\sqrt{\frac{\varepsilon_{mr} n_a^2}{\varepsilon_{mr} + n_a^2}} \tag{2}$$

$$k_{SPP}^2 = n_a^2 k_0^2 \sin^2\theta + \left(m\frac{\lambda}{\Lambda}\right)^2 \pm 2n_a m\frac{\lambda}{\Lambda}k_0 \sin\theta\cos\varphi \tag{3}$$

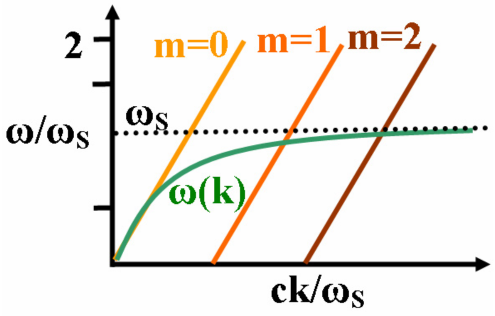


Fig. 3. Grating coupler based on SPR dispersion curves.

C. Periodic surface and SP photonic bandgap:

The band structure of a given surface plasmon photonic defines its optical properties, such as transmission, reflection, and angular dependence. Spatial distribution of an electromagnetic field can be manipulated in a SP photonic bandgap to produce local field enhancement in dielectric. The field enhancement in a nonlinear SP photonic bandgap can be utilized to enhance nonlinear optical effects that are strongly dependent on the local field. This behavior is shown in Fig. 4. Periodic texturing of the metal surface can lead to the formation of as SP photonic bandgap, at the band edges the density of SP states is high, and there is a significant increase in the associated field enhancement [21-23].

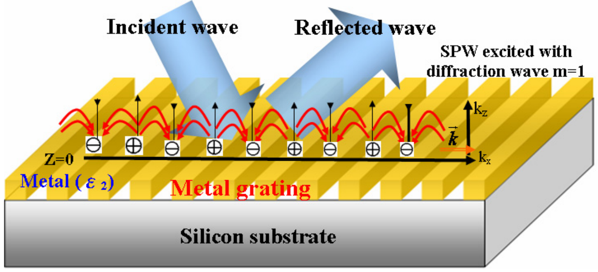


Fig. 4. Excitation of SP wave on a periodically modulated surface of metal grating SP photonic bandgap propagation.

Ⅲ. SENEOR CHIP FABRICATION

A. Device Design:

The samples are prepared by Electron Beam Lithography system. The EBL ELS-7500EX is scanning electronic microscope (SEM) equipped with a lithographic system. The incident electron beam was 50KV of the acceleration voltage. In a first step, we used the electron-beam resist ZEP520A (To-Nippon Zeon Co.) high resolution positive electron beam resist, by spin coated a 100nm thick resist layer on silicon substrate, and pre bake temperature 180℃ for 2 minutes. After exposure of the substrate to the electron beam of the exposed ZEP520A. The shape of the individual grating was slightly elongated line one-dimensional patterns of nanostructures grating 200nm, pitch 400nm, exposure area 1.2x1.2mm, pixel map 60000x60000 dots, dose timer 2 μ sec. Next, a Cr film 5nm and gold film 50nm was by e-beam evaporated deposited onto the grating, with an evaporation rate of approximately

0.2 Å/s. Then, the remaining ZEP520A resist layer is removed by N,N Di-methylacetamide (ZDMAC, To-Nippon Zeon Co.) into a washing solution, Liftoff the gold films on ZEP520A resist. The patterning process is illustrated as show in Fig 5.

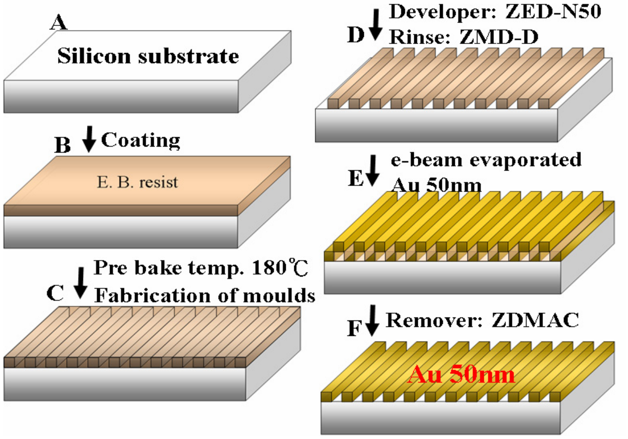


Fig. 5. Schematic flow diagram of the nanostructures patterning of metallic symmetrical lamellar grating thin films.

The sensing layer is for the detection of small quantities of a given substance, the grating surface has to be functionalized in order to specifically bind the target molecules to it. For each molecule to be analyzed, a specific counterpart is needed. Every molecule, for which a selective counterpart is found, may in principle be measured with the sensor system. An illustration of the recognition process on the chip surface is show in Fig 6.

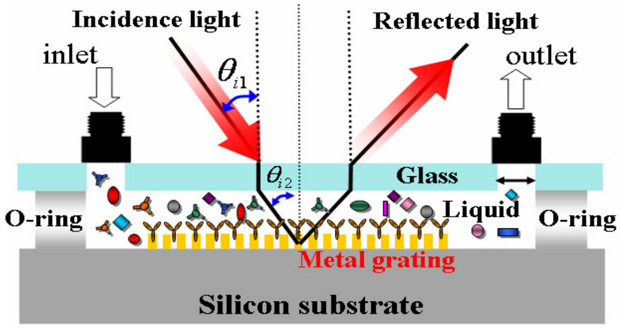


Fig. 6. Metallic grating surface on Bio-chemical adlayer sensing.

B. Measurement system setup:

The reflectivity measurement system for Grating experiment was performed at room temperature using the setup seen in Fig. 1. A white light source (Newport Oriel Spectral Luminator 69050) is used TM-polarization direction filter into illuminate the coupling grating chip. The beam shape is controlled with a focus lens of large focal distance. The grating chip is placed in the center of rotation of a high resolution rotary table measuring angle (φ). The out coupled beam is through a 2 inch the focal distance 5cm lens on a spectrometer (Ocean Optics Co.) or CCD measuring out coupled optical change in ambient refraction index resulted in the observable shift of the angle (θ) and intensity change in the reflectance.

IV. RESULTS AND DISCUSSION

A. 1D metal grating nanostructure by E-Beam lithography

The patterning process is illustrated in Fig. 5 we used an EB resist mould with 1D line patterns, which was fabricated by EB lithography. Fig. 7 shows the top-view field emission SEM (ELS-7500EX, ELIONIX CO.) images of patterned exposure gold thin films. Their surface profiles measured with atomic-force microscopy (AFM) are shows in Fig. 8. The grating profiles calculated with the unified method are shows in the figures, too. The grating heights of the AFM profiles agree well with those of the calculated profiles.

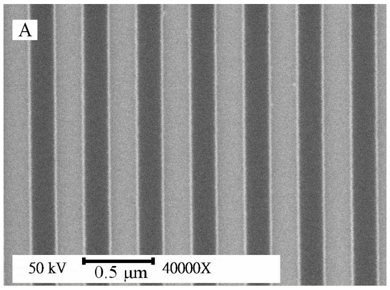
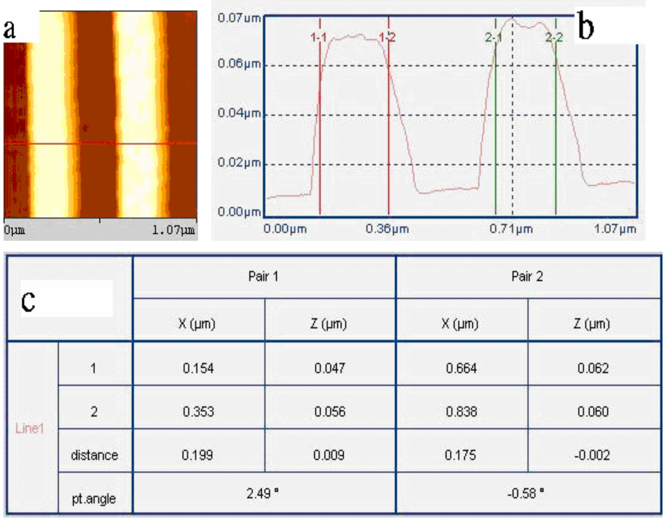


Fig. 7. The SEM of the fabricated grating and results for the line-200nm and pitch-400nm period grating.



		Pair 1		Pair 2	
		X (μm)	Z (μm)	X (μm)	Z (μm)
Line1	1	0.154	0.047	0.664	0.062
	2	0.353	0.056	0.838	0.060
	distance	0.199	0.009	0.175	-0.002
	pt.angle	2.49 °		-0.58 °	

Fig. 8. The grating profiles (a) are used to check the shape, lateral size, and height (b, c) of the structure by AFM.

B. Resonance angle measurements on metal grating nanostructure

The resonance angle measurements on metal grating, changes in SPR were measure from the angular spectrum as show in Fig. 9. The angular spectrum was cut-out from the CCD detector.

This allows us to measure the experimental angle-dependent reflectivity as show in Fig. 10. Incident light beam of different wavelength 530nm, 643nm and 833nm on a grating of this pitch permits momentum enhancement such that two SPR angles appear. These are the first and second order resonances, where the number and sign refer to the diffracted order that provides the resonant coupling to the SPP.

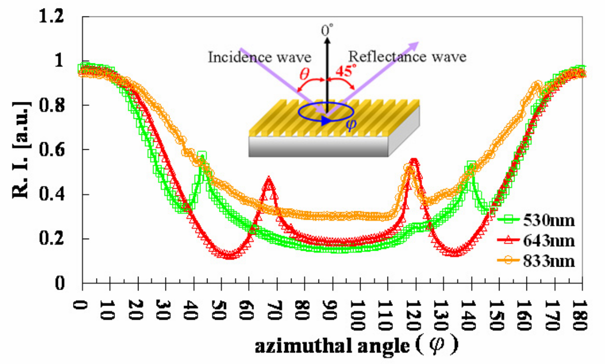


Fig. 9. Illustrate the azimuthal-angle-dependent scans at θ=45 degree, Two minima in reflectivity can be observed which are attributed to the coupling to a surface plasmon in first and second order.

The resonance peaks for the in coupling grating were rotary table measuring angle φ=0 degree, the intensity of the reflected light beam is recorded on the different angle (θ= 5~25 degree, φ=0 degree) of observation. The SPR signal was measure as a change in the angular distance between the SPR dips in the angular spectrum as show in Fig. 10.

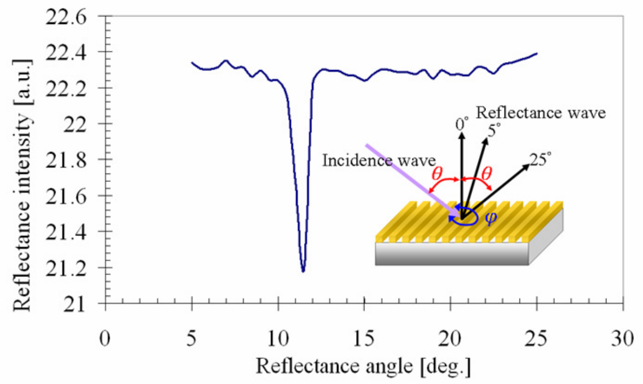


Fig. 10.The measured of the reflected light angle from the metal grating for TM-polarised light with a wavelength of 530nm.

V. CONCLUSIONS

In this study, we investigated the nanostructures metallic grating by using electron beam lithography of SPR on optical Biosensor. We have shown experimentally that strong coupling between electronic and photonic resonances in metallic grating plasmon resonances in gold nanowire arrays leads to the formation of a SPP bio-sensing device. This novel effect is a suitable tool for SP photonic band gap engineering in active photonic crystals. In experiments we showed that SP-coupled emission also occurs with grating gold films, we will making this technology applicable to any assay using metal grating films such as SPR to measure bioaffinity reactions. Therefore, further investigations are and will be performed.

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