Surface plasmon resonance via polarization conversion in a weak anisotropic thin film

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A columnar structured thin film with weak anisotropy is applied to trigger the electromagnetic wave with forbidden polarization state to excite surface plasmon. The precursory work is done here for the conventional Kretschmann configuration [D. Sarid, Phys. Rev. Lett. **47**, 1927 (1981)] by arranging an anisotropic thin film in the configuration as a three-layered system (prism/anisotropic dielectric film/metal film/isotropic thin film/air). It enables both *p*-polarized and *s*-polarized incident waves simultaneously to excite surface plasmon. © *2009 American Institute of Physics*.
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Surface plasmons have been the subject of growing interest over the years because of their potential in optics and biological sensing.[1–3] Surface plasmon is essentially an electromagnetic wave that is trapped and propagating along the interface between metal and dielectric medium.[4,5] Localized surface plasmon is a related phenomenon associated with the coupling effect between electromagnetic wave and oscillation of free electrons in metal particles. The prerequisite to excite surface plasmons is the polarization of the electromagnetic wave. In this work, we propose a method that using an anisotropic thin film could trigger the forbidden polarized wave to excite surface plasmon resonance (SPR). The precursory work is done here for the Kretschmann configuration[4] that is well known and widely applied for exciting a two-dimensional surface plasmon by matching the wave vector of the incident light in a high-refraction-index prism to the wave vector of the surface plasmon wave. The prerequisite for conventional SPR is that the obliquely incident light must be *p*-polarized. Arranging an anisotropic thin film between the coupling prism and the metal film enables *p*-polarized and *s*-polarized waves simultaneously to excite surface plasmon.

The proposed configuration is similar to the configuration that generates a long-range surface plasmon:[5] a three-layered BK7 prism/anisotropic dielectric film/metal film/isotropic thin film/air system presented in Fig. 1(a). The anisotropic SiO_2 thin film is grown on a BK7 substrate using electron beam evaporation with glance angle deposition[6–9] at which deposition occurs at a tilt angle with respect to the direction of the deposited flux. The deposition rate is 0.3 nm/s and the deposition angle is 70°. The anisotropic thin film is a tilt columnar structure because of the self-shadowing effect, and the column angle between the surface normal and the columnar growth direction is $\beta=28°$. The deposition plane, defined by the column growth direction and the surface normal, makes an angle δ from the plane of incidence. The anisotropic thin film exhibits weak birefringence[9–11] with one of its principal axes in the columnar growth direction, as shown in Fig. 1(b). The three associated principal indices (n_1, n_2, n_3) for a wavelength of 632.8 nm are measured as 1.3438, 1.301, and 1.3049. In our previous work,[10,11] the weakly birefringent thin film in a single-layered (prism/film/air) system promotes conversion of polarization: since the deposition plane is not coincident with the plane of incidence, the polarization state of the reflected beam is altered from that of the oblique incident beam. The reflectance angular spectrum indicates enhanced polarization conversion. Over 90% of *p*-polarized incident light may couple to the reflected *s*-polarized light within a particular range of incident angles that exceed the critical angle.[10] The anomalous phenomenon combines phase retardation, interference, and total reflection mechanisms which occur in the anisotropic thin film in the three-layered system.

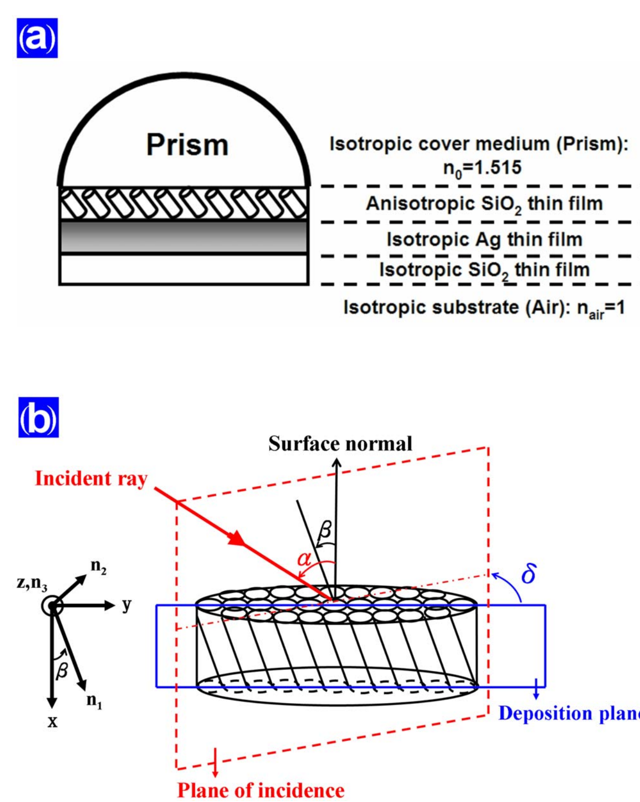

FIG. 1. (Color online) (a) Three-layered BK7 prism/anisotropic dielectric film/metal film/isotropic thin film/air system. (b) Relationship between plane of incidence and deposition plane: β is the column angle and α is the angle of incidence.

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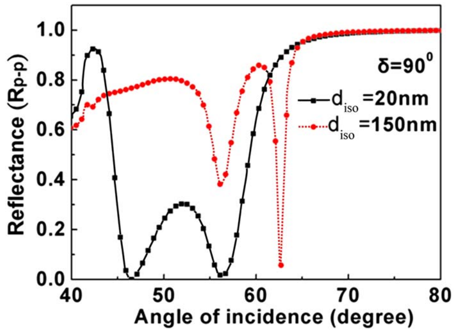

FIG. 2. (Color online) Reflectance angular spectra of the configuration for two thicknesses of the isotropic SiO_2 film: $d_{iso}=20$ nm and $d_{iso}=150$ nm. The aspect of deposition plane is $\delta=90°$.

The silver film in the three-layered configuration is grown on the columnar structured SiO_2 film with normally incident deposition flux. Since the thickness of the silver film is small (only 26.4 nm), tips of SiO_2 columns are embedded in the film. The effective index of refraction n' and the index of extinction k' of the silver-SiO_2 composite film can be derived as $(n'=0.561,\ k'=3.963)$ by fitting the reflectance angular spectrum. The effective dielectric constant of the silver film is $\varepsilon'+i\varepsilon''=-15.390+4.446i$.

The isotropic SiO_2 thin film that is adjacent to the silver thin film is adopted to tune the excitation state of surface plasmon. The wave vector of the surface plasmon propagating along the isotropic SiO_2/silver interface is given by

$$k_{SP}=\frac{2\pi}{\lambda}\sqrt{\frac{\varepsilon_{iso}\varepsilon'}{\varepsilon_{iso}+\varepsilon'}}, \quad (1)$$

where λ is the wavelength of light *in vacuo*. The wavelength of 632.8 nm from a He–Ne laser is used for simulation and discussion in this paper. ε_{iso} is the dielectric constant of the isotropic medium that is adjacent to the silver film; ε' is the real part of the dielectric constant of the silver film. As the thickness of the isotopic thin film increases from zero to infinity, the wave vector in Eq. (1) increases from $k_{SP}(\varepsilon_{iso}=\varepsilon_{air})$ to $k_{SP}(\varepsilon_{iso}=\varepsilon_{SiO_2}=2.0449)$ because the surface plasmon resonates in two extreme cases: one is when an infinite extended air is adjacent to the silver; the other is when the SiO_2 that is adjacent to the silver extends infinitely. The SPR is observed from the attenuated total reflection (ATR) dip in the angular reflectance spectrum of the configuration. The p-polarized reflectance angular spectra of the three-layered configuration are simulated for two thicknesses of the isotropic SiO_2 films with index of refraction of 1.430: $d_{iso}=20$ nm and $d_{iso}=150$ nm, respectively, as shown in Fig. 2. The deposition plane aspect is $\delta=90°$ so enhanced polarization conversion occurs around the angles of incident 53°–60°. The reflectance R_{i-j} $(i,j=s,p)$ refers to the extent to which the intensity of the reflected j-polarized beam exceeds that of the incident i-polarized beam. The p and s subscripts are the usual polarization designators for p- and s-polarization, respectively. The R_{p-p} ATR dip is estimated to vary from 47.0° to 62.7° as the thickness d_{iso} increases from 20 to 150 nm. Therefore, the isotropic SiO_2 film with index of refraction of 1.430 and thickness of 74.6 nm is fabricated on the silver film to match the condition for polarization conversion. In the matched case, the polarization conversion and surface plasmon resonate simultaneously around the angle of incidence of 56.5° and the associated angular spectra R_{i-j} is measured and presented in Fig. 3(a). The reflectance R_{s-s} becomes an ATR curve for s-polarized incidence that is associated with SPR on the silver/isotropic medium interface.

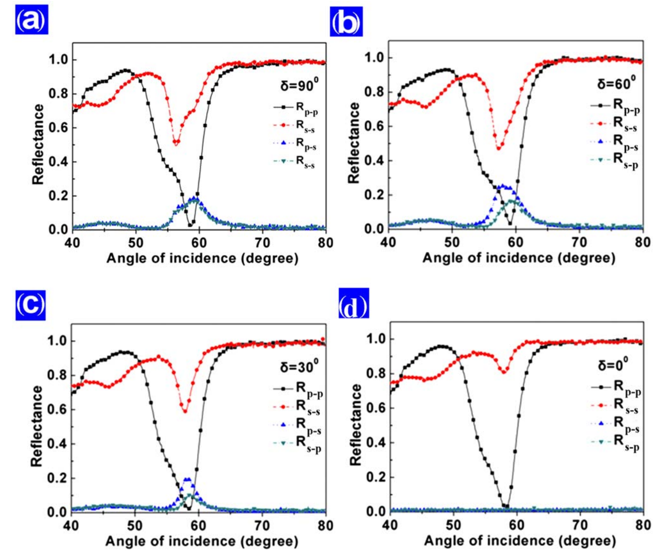

FIG. 3. (Color online) Measured reflectance angular spectra R_{i-j} $(i,j=s,p)$ of the configuration at wavelength of 632.8 nm for deposition plane aspects of (a) $\delta=90°$, (b) $\delta=60°$, (c) $\delta=30°$, and (d) $\delta=0°$.

The aforementioned three-layered film stack is fabricated on a BK7 substrate, and the substrate is attached to a BK7 prism with index-matched oil to yield a BK7/aniostropic SiO_2 film/Ag film/air configuration. Therefore, the substrate with the film stack is rotatable. Figures 3(b)–3(d) present the reflectance R_{i-j} for $\delta=60°$, $\delta=30°$, and $\delta=0°$, respectively. The figures indicate that the polarization conversion effect declines as the film is rotated from $\delta=90°$ to $\delta=0°$. At the aspect $\delta=0°$, the reflectance spectrum shows only a p-polarized ATR dip.

Under the condition that the aspect of the deposition plane is at $\delta=90°$, Fig. 4 plots the absorption as a function of incident angle A_P for a p-polarized incident wave and A_S for an s-polarized incident wave. At an angle of incidence of 56.5°, 11% of the s-polarized incident light is coupled to the p-polarized reflected light and 12% of the p-polarized incident light is coupled to the s-polarized reflected light. 50% of the s-polarized incident light, which is still reflected as s-polarized light, and 39% of the s-polarized incident light are absorbed by the silver dissipation and SPR. 30% of

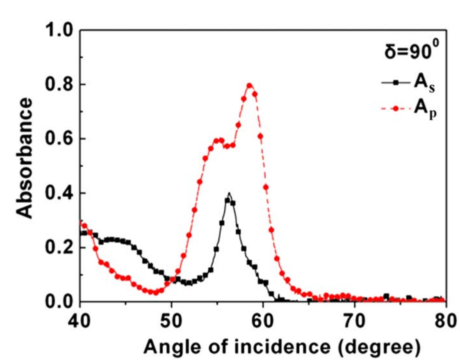

FIG. 4. (Color online) Absorption vs incident angles A_P and A_S for p-polarized incident beam and s-polarized incident beam.

p-polarized incident light is still reflected as *p*-polarized light and 58% of *p*-polarized incident light is absorbed by the silver dissipation and SPR.

In conclusion, in an experiment, a widespread columnar thin film arranged in the Kretschmann configuration causes incident *s*-polarized light to excite a surface plasmon. The reflectance angular spectrum exhibits both *s*-polarized and *p*-polarized ATR dips associated with SPR. Various *s*-polarization induced SPR can be tuned just by rotating the deposition plane or plane of incidence. The configuration shown herein supports the concept that the restriction on the polarization state to excite SP can be lifted by coating an obliquely anisotropic thin film on any plasmonic structure and therefore opens a design path worth exploring.

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