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Modulation of Surface Plasmon Resonance by Magnetization Reversal in Au/Fe/Au Trilayer and Wedge Structure toward Higher Refractive Index Sensitivity

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Abstract

We report on enhancement of the transverse magneto-optic Kerr effect (TMOKE) in Au/Fe/Au trilayers for improving the refractive index (RI) sensitivity in surface plasmon resonance (SPR) sensors by magnetic modulation. The thicknesses of the upper Au, Fe, and lower Au layers are optimized, for maximizing TMOKE intensity. Tuning the metal layer thickness and SPR is demonstrated in a single sensor chip composed of a wedge Au thin film. Enhancing the RI resolution is expected in sensor chips with Au/Fe/wedge Au trilayer.

1. Introduction

Surface plasmon polaritons (SPP) are quasiparticles by collective electron oscillations coupled to lightwaves at the interface between a metal and a dielectric, which enables strong optical confinement at the interface. Slight change of the refractive index (RI, n) of the dielectric modifies the propagation constant, which has been applied to surface plasmon resonance (SPR) bio- and gas-sensor through measuring RI at the metal surface [1]. Recently, fast, label-free, and highly sensitive detection of volatile organic compounds (VOCs), and SARS-CoV-2 coronavirus, has been strongly required. RI resolution of 10^{-6}~10^{-8} is required to meet these demands.

Highly conductive metals (Au, Ag) have been used to excite SPP and applied to sensing chips in SPR sensor. It has been demonstrated that the propagation constant of SPPs can be modified by transverse magneto-optic Kerr effect (TMOKE). Enhancement of the sensitivity in SPR sensors with ferromagnetic metals (FMs) has been reported by modulating the resonance condition through magnetization reversal [2]. However, FMs cause the propagation loss as well as magnetic modulation, leading to reduced sensitivity. Loss of SPPs with FMs is much larger than that with noble metals (NMs; Au, Ag), owing to their higher ohmic loss than those of NMs. So far, combination of NMs with FMs has been extensively studied, where the MO effect is implemented by FMs whereas relatively lower losses of SPPs are realized by NMs, leading to enhanced sensitivity of SPR sensors [2, 3].

Momentum matching between the in-plane component of the wavenumber of the incident light and the wavenumber k_{SPP} of SPP, as well as magnetic modulation, is important for enhancing the sensitivity. We have reported that TMOKE intensity with an attenuated total reflection (ATR) setup defined as the reflectivity change normalized by the sum of the reflectivity for p-polarized light upon the magnetization reversal, $\Delta R/R$ = ($R(+M)$ - $R(-M)$) / ($R(+M)$ + $R(-M)$), were nearly 100 % owing to the perfect momentum matching in double dielectrics and ferromagnetic metal (DDFM) structures composed of Al_2O_3 / SiO_2 / Fe [4]. When $\Delta R/R$ is defined as the sensor signal, the sensitivity can be expressed as $(\partial(\Delta R/R))/\partial n$. Since $(\partial(\Delta R/R))/\partial n=(\partial(\Delta R/R))/\partial\theta \cdot \partial\theta/\partial n$, not only RI displacement $\partial\theta/\partial n$, but also the sharpness $(\partial(\Delta R/R))/\partial\theta$, is important for higher RI sensitivity [5].

In this paper, we report modulation of SPR by magnetization reversal in Au/Fe/Au trilayers and method to realize larger sharpness $(\partial(\Delta R/R))/\partial\theta$, with wedge Au thin film.

2. Magnetic Modulation of SPR in a Au/Fe/Au trilayer

Fig. 1 shows the structure of SPR transducer of a Au/Fe/Au trilayer on a quartz glass substrate. The wavelength of the incident light is 632.8 nm. The thickness of the Fe layer was set at 3 nm in order to realize continuous Fe film providing magnetic modulation through TMOKE. The thickness set of the upper and lower Au layer (t_{Au1}, t_{Au2}) was

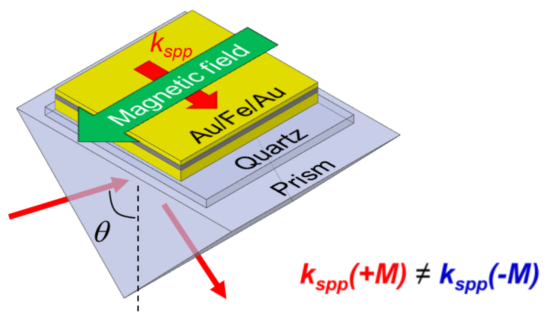

Fig. 1 A schematic image of the Au/Fe/Au trilayer for magnetic modulation of SPR and ATR setup for characterization.

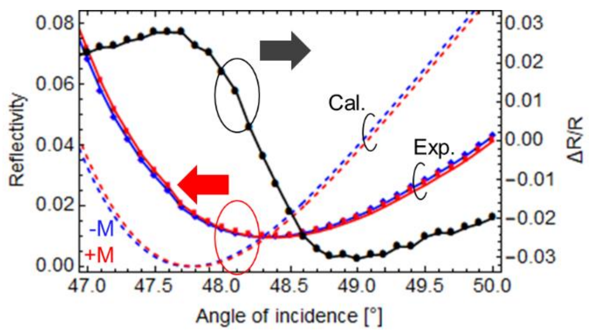

Fig. 2 Incident angle dependence of the reflectivity (left axis) of the trilayer structure upon the magnetization reversal and TMOKE intensity $\Delta R/R$ (right axis). Calculated reflectivity are shown with dotted curves.

designed by maximizing $\Delta R/R$ upon the magnetization reversal with a combination of the layer thicknesses with a unit of 1 nm [6], and was obtained as (t_{Au1}, t_{Au2}) = (4, 22 nm). The upper Au layer reduces the propagation loss by Fe and prevents the oxidization of the Fe layer. The lower Au layer prevents the evanescent wave from radiation at the quartz glass substrate.

The trilayer was prepared by electron-beam (EB) evaporation on a quartz glass substrate. Coercive force $\mu_0 H_c$ of the sample is 4 mT by measuring the TMOKE under magnetic field applied with a Helmholtz coil. The average roughness of the metal surface is 1.4 nm by an atomic force microscopy (AFM), which is smaller than the Fe layer thickness (3 nm). The sample was mounted on a right-angle quartz prism with an index-matching oil for ATR setup. Collimated p-polarized light from a He-Ne laser was introduced to the sample mounted on a stepping motor with a rotating angle resolution of 0.1 °, and reflected light was detected by a Si PIN photodiode. Fig. 2 shows the incident angle dependence of the reflectivity and TMOKE intensity $\Delta R/R$ under magnetic field of +/- 0.1 T by a permanent magnet. The calculated reflectivity was plotted for designed trilayer structure. The minimum reflectivity R_{min} was 0.01, and the angle θ_{SPR} providing R_{min}, were 48.4° and 48.3° for magnetic field of +/- 0.1 T. Maximum $\Delta R/R$ is 3 %. Both R_{min} and θ_{SPR} are slightly larger than those of the calculated results. With increasing t_{Au2}, θ_{SPR} becomes smaller owing to the difference of the momentum matching condition. Therefore, the reason for the difference is that the deposited metal layer is slightly thinner than the designed metal layer. A specific t_{Au2} satisfies the perfect momentum matching condition, making R_{min} smaller. Tuning t_{Au2} leads to larger sharpness $(\partial(\Delta R/R))/\partial\theta$.

3. Modulation of SPR in a wedge Au thin film

In order to tune t_{Au2} in a single sensor chip, and realize larger sharpness for enhancing the sensitivity, we have developed a wedge Au thin film on a glass substrate as shown in Fig. 3. The sample was fabricated with EB evaporation by controlling the position of shutter inside the chamber during deposition process. The minimum and maximum thickness ($t_{Au,\,min}$ and $t_{Au,max}$) were set at 40 and 50 nm.

The reflectivity was measured by CMOS camera with introduction of the cylindrical lens for measuring the incident angle dependence of the reflectivity. Obtained image is the inverted image along horizontal direction. Fig. 4 shows the luminance distribution from the wedge Au thin film. A dark area can be found between the bright area, corresponding to the minimum reflectivity with θ_{SPR}. With increasing t_{Au}, the position of the dark area shifted to smaller θ. The luminance of the dark area is larger at the region of t_{Au} = 40 nm, compared with that of t_{Au} = 50 nm, showing that the minimum reflectivity was tuned at the region of t_{Au} = 40 – 50 nm. Combining the magnetic modulation and tuning t_{Au2} in Au/Fe/wedge Au trilayer, enables to enhance the sharpness.

4. Conclusions

We reported the design and demonstration of the magnetic modulation of SPR in a Au/Fe/Au trilayer for enhancing the sensitivity by using a TMOKE intensity $\Delta R/R$ as a sensing signal. We have tuned the metal layer thickness in a single chip by fabricating a wedge Au thin film. Enhancing the sharpness $(\partial(\Delta R/R))/\partial\theta$ and RI resolution can be demonstrated by a sensor chip of Au/Fe/wedge Au trilayer. The method to enhance the RI sensitivity is effective in SPR sensors with localized surface plasmon by FM / NM nanostructures [3]. Magnetization switching by nonlocal spin injection to nanoscale FMs [7] without external magnet would realize highly sensitive, compact and integrated point-of-care (PoC) devices for detecting VOCs and SARS-CoV-2.

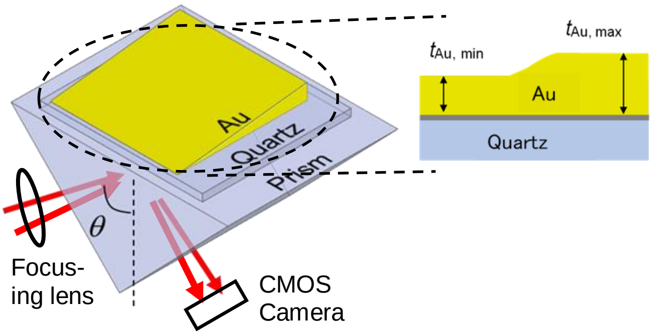

Fig. 3 A schematic image of a wedge Au thin film and ATR setup with focusing lens and CMOS camera.

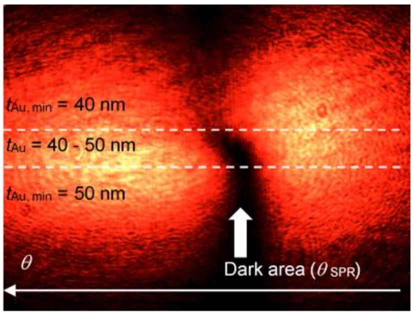

Fig. 4 Luminance distribution from the wedge Au thin film.

Acknowledgements

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