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Strong Light Confinements of Dielectric-Assisted Surface Plasmons Based on ZnO in the Infrared Range

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Abstract

We have reported roles of Ga_2O_3 dielectrics to strong light confinements on ZnO-based surface plasmon resonances (SPRs). Oxide semiconductors are expected to be promising for infrared SPR excitations, which can realize propagated SPR modes on two-dimensional layer surfaces in replace of localized SPR modes based on nanoantennas. This is benefit for sensing and waveguide applications. ZnO-based SPRs exhibited high performance of SPR in the infrared range by insertions of Ga_2O_3 dielectrics on ZnO: Ga layers, providing formation of strong electric-fields. This study provides new information to obtain efficient SPR responses in the infrared range based on engineering of dispersion curve.

1. Introduction

Surface Plasmons (SPs) have been applied to observe chemical binding of molecules in biochemical fields, which have been realized using noble metals (e.g.; Au and Ag) [1]. In particular, SPRs in the infrared (IR) range have attracted much attention for bio-sensing applications based on the molecular fingerprints. For instance, nano-antenna structures is famous and promising method to excite infrared SPRs and the structures can make it possible to control excitation wavelength of SPRs in IR regions by changing the length of nano-antenna and the gap between nano-antennas. However, light confinements onto layer surfaces are weak due to the dispersion relations of noble metals since nano-antenna structures have been used to excite infrared SPRs.

In contrast, oxide semiconductors are one of promising materials to control SPR excitations in the IR range by control of free carriers [2], indicating dispersion engineering dependent on material-type. This method aims at being excited SPRs efficiently in the IR range for bio-sensing applications. Recently, we achieved strong light confinements in the IR range without nano-antenna structures using dielectric-assisted SPR with metallic ZnO: Ga layers, which will be presented from viewpoints of SPR properties and sensing performance.

2. Role of Ga_2O_3 dielectrics in ZnO-based SPRs

SPR excitations on single ZnO: Ga layer surfaces have provided weak electric-fields (*E*-fields) strengths on ZnO: Ga surfaces [3]. This weak SPR response has further been improved using asymmetric ZnO: Ga structures with an insulator-metal-insulator (I-M-I) [4]. This structure has played an important role in producing strong *E*-fields on the ZnO: Ga layer surfaces. It is known that an I-M-I structure shows a long-range SPR mode, providing spatially extended an *E*-field because a long-range SPR show a characteristic of an electromagnetic wave. As a consequence, *E*-fields could not be strongly confined on ZnO: Ga layer surfaces in the NIR region. In an effort to achieve a strong *E*-field and a high light confinement, we introduced Ga_2O_3 dielectrics on ZnO: Ga layer surfaces. A Ga_2O_3 dielectric has a high refractive index (*n*) and a small extinction coefficient (*k*), which contribute to high transparency in the NIR region. In general, a metallic layer for SPR excitation is commonly damped through a high *k* value. However, hybrid Ga_2O_3/ZnO: Ga layer structures provide strong *E*-fields with small field depths because a Ga_2O_3 dielectric has an extremely low *k* value as compared to metals. In this paper, we present dielectric-assisted SPR platforms based on ZnO: Ga in the NIR region. Role of a Ga_2O_3 dielectric to ZnO-based SPR devices will be cleared from experimental and theoretical aspects.

3. Theoretical calculations based on Fresnel Equations

E-fields ($<E_{zz}^2>$) perpendicular to the sample surfaces were calculated using Fresnel Equations [5]. A calculated sample comprised a hybrid structure of water-Ga_2O_3-ZnO: Ga-cytop polymer. Thicknesses ZnO: Ga and cytop layers were 22 nm and 2200 nm, respectively. A value of $<E_{zz}^2>$ gradually increased with increasing Ga_2O_3 layer, and then

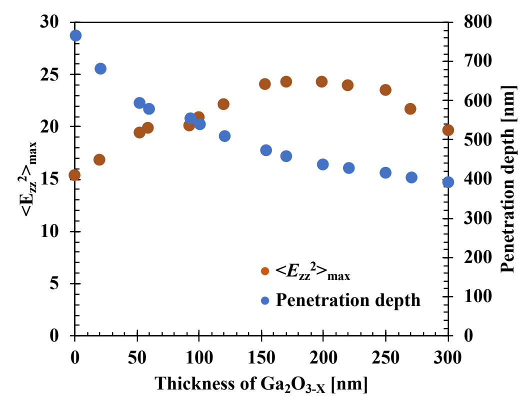

Fig. 1. $<E_{zz}^2>$ and penetration depth as a function of Ga_2O_3 thickness on the hybrid structures. A sample was consisted of water-Ga_2O_3-ZnO: Ga-cytop polymer.

showed a maximum value at a layer thickness of 200 nm [Fig. 1]. On the other hand, a penetration depth monotonically decreased with increasing Ga_2O_3 layer. Insertions of Ga_2O_3 on ZnO: Ga layer surfaces realized strong *E*-fields with small penetration depths. Furthermore, we found change in propagation type from surface plasmon to waveguide modes [Fig. 2]. Cross-over in mode change was in thickness range 500 to 600 nm. Some high-order TM modes in terms of waveguides appeared in addition to a common SPR mode, which exhibited sharp peak structures.

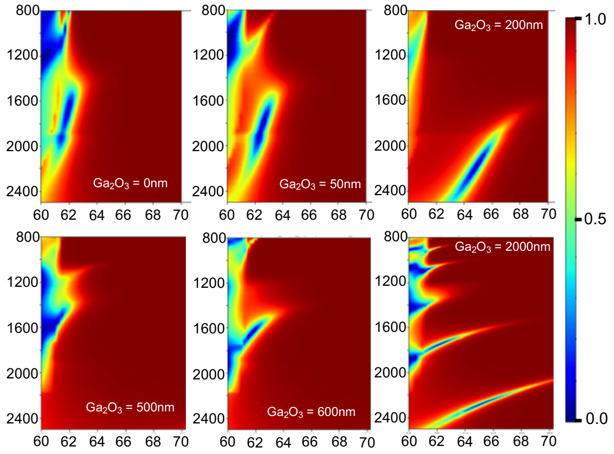

Fig. 2 Theoretical dispersion curves of TM-polarized light in the hybrid structure. A horizontal axis represents an angle of incident light from 60 to 70 degrees. A vertical axis indicates a wavelength of incident light from 800 to 2500 nm.

4. Experiments and discussion

We prepared a hybrid structure consisting of cytop, ZnO: Ga and Ga_2O_3. Cytop is one of a fluorine-containing resin, which was coated using spin-coating. On the other hand, ZnO: Ga and Ga_2O_3 layers were deposited using a pulsed laser deposition. Fig. 3(a) exhibits a schematic picture of the fabricated hybrid structure, which was also confirmed by surface SEM and X-TEM images [Fig. 3(b)]. Angular and wavenumber-dependent SPR spectra were FT-NIR with Kretschmann-type ATR, as shown in Fig. 3(c). The peak positions systematically shifted to higher wavenumbers with increasing incident angle (θ), as reflected by the dispersion curve of SPR, which were reproduced using theoretical calculations [Fig 3(d)]. The difference between experimental and calculated data was related to structural inhomogeneity from the TEM image. Besides, a cross-section profile of $\langle E_z^2 \rangle$ strength on the hybrid sample was depicted in Fig 3(e), revealing that a strong *E*-field on a Ga_2O_3 layer surface. This behavior was largely different from a common dielectric-based waveguide structures. An employment of Ga_2O_3 led to enhanced SPR responses because of suppression of plasmon damping induced on metallic ZnO: Ga layer surfaces. Use of dielectrics to SPR platforms played an important role in obtaining high performance of SPR, which also provided new structure concept to realize strong *E*-fields on layer surfaces in the IR range for bio-sensing applications.

3. Summary

ZnO-based SPR have exhibit high performance of SPR in the IR range by insertions of Ga_2O_3 dielectrics on a ZnO: Ga layers, resulting in formation of strong *E*-fields, which are demonstrated from experimental and theoretical approaches. This work provides optical design to obtain high sensing activity in the NIR range without nano-antenna structures being requested EB lithography.

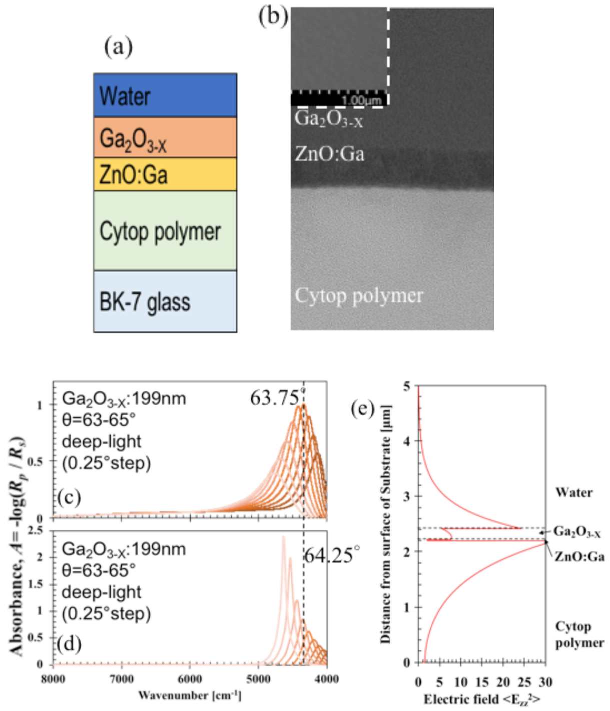

Fig. 3 (a) Schematic picture of the hybrid structure. (b) Cross section TEM image TEM. Insert indicates a surface SEM image on Ga2O3 layer surface. Experimental (c) and calculated (d) SPR spectra. (e) Electric field strength at the distance from the surface of substrate.

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