Excitation of Surface Plasmon Polariton at the GaP–Au Interface in a High-Refractive-Index Medium

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Abstract: We demonstrated the application of GaP–Au contacts as SPP chemical sensors for a high-refractive-index medium, as verified using 2,4-dichlorotoluene ($C_7H_6Cl_2$, n = 1.55). The calculation of the dispersion relationship shows that the surface plasmon polariton (SPP) excited in GaP for incident light (λ = 635 nm) illuminated at 31.6° can be effectively used for detecting $C_7H_6Cl_2$. Subsequently, reflectance is analyzed as a function of Au thickness. The SPP excitation angle determined experimentally is found to be consistent with that of simulation data. When light is illuminated at 31.6°, the electric field is concentrated at the interface between Au and $C_7H_6Cl_2$ and is propagated along the interface. These results suggest that the SPP excited at the GaP–Au interface can be used as chemical sensors.

Introduction: In semiconductor electronic devices such as the Schottky barrier diode, the metal–semiconductor junction can act both as the Schottky contact and ohmic contact. In principle, the refractive index of a semiconductor is higher than that of transparent materials such as glass and sapphire, making semiconductors such as GaP and GaN transparent in the visible and near-ultraviolet-light regions. The combination of a semiconductor and a metallic thin film might result in the excitation of SPP at the metal–semiconductor interface. Typical examples of the application of SPP using metal and semiconductor include a silicon photodiode and luminescence enhancement of visible light light-emiiting diodes[1, 2]. On the other hand, the Kretschmann arrangement on the basis of the attenuated total reflectance method has been applied to chemical sensor. However, to use total reflection, it is difficult to detect the light reflected from a medium having a refractive index higher than 1.5, such as 2,4-dichlorotoluene ($C_7H_6Cl_2$, n = 1.55) and 1-bromonaphthalene ($C_{10}H_7Br$, n = 1.65). In this study, we focused on the semiconductor GaP, which is transparent in the visible region, has a large refractive index (3.3), and exhibits a wide band gap (2.2 eV). Its application as a chemical sensor has been attempted using the excitation of SPP at the interface between GaP and a metallic thin film. However, to the best of our knowledge, there are no detailed studies reported so far on the analysis of excitation conditions of SPP at the interface between the metal and semiconductor. In this study, we theoretically and experimentally analyzed the dependence of reflectance on the incidence angle for the interface between GaP and the Au thin film.

Calculation of Dispersion Relationship and Reflectance: When the complex dielectric constant of metal is $\varepsilon_1 = \varepsilon_1' + i\varepsilon_1''$ and that of a dielectric is ε_2, the dispersion relation at the interface of metal and dielectric is given by the following equation[3].

$$k_{sp} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_1'\varepsilon_2}{\varepsilon_1' + \varepsilon_2}} + i\frac{\omega}{c}\left(\frac{\varepsilon_1'\varepsilon_2}{\varepsilon_1' + \varepsilon_2}\right)^{\frac{3}{2}} \tag{1}$$

$$k sin\theta = \frac{2\pi n\, sin\theta}{\lambda_0} = \Re e\{k_{sp}\} \tag{2}$$

The dispersion relationship is calculated for Au-$C_7H_6Cl_2$ with n = 1.55. Fig.1 shows the dispersion relationship between Re{k_{sp}} and ω. The laser light of wavelength 635 nm was used for the analysis. The angular frequency (ω_{sp}) of the exciting light is found to be $\omega_{sp} = 2.95 \times 10^{15}$ rad/s. The wavenumber k_{sp} for the exciting surface plasmon polariton (SPP) is obtained from the intersection of the dispersion curve and the light line. Furthermore, the incident angle θ in the substrate is obtained from the following eq. (2), where k is the wavenumber of the substrate, λ_0 is the wavelength in vacuum, and n is the refractive index of the substrate. According to the dispersion relationship of Au-$C_7H_6Cl_2$, it is estimated that GaP can excite SPP at 31.0°. However, SiO_2 cannot excite the SPP.

Furthermore, the dependence of reflectance on the incident angle is calculated by the rigorous coupled wave analysis (RCWA) method. Fig.2 shows the dependence of reflectance on the incident angle for GaP/Au/$C_7H_6Cl_2$. Light of wavelength 635 nm is illuminated from the GaP substrate. The critical angle between GaP and $C_7H_6Cl_2$ is 27.9°, for which there is a rapid increase in reflectance. For an incident angle of 31.6°, reflectance decreases. In particular, the reflectance is close to 0 for 50-nm-thick Au.

Experimental Results and Discussion: The abovementioned results for GaP/Au/$C_7H_6Cl_2$ were further substantiated via fabricating a GaP–Au contact and performing reflectance measurement. The sample was fabricated by sputtering Au (MC-701, SANYU) onto a GaP (100) single crystal substrate. The dependence of reflectance on the incident angle was measured, as the p-polarized light is allowed to enter from the GaP side toward Au. The corresponding experimental results are shown in Fig.3. The reflectance becomes minimum at 31.1°, at which the SPP is excited at the Au-$C_7H_6Cl_2$ interface. This result is almost consistent with the simulation data.

Subsequently, we calculated the distribution of electric and magnetic fields when the SPP is excited. Fig.4 shows the distribution of electric field for the incident angle of 31.6°, as simulated by the RCWA method. The electric field is concentrated at the interface between Au and $C_7H_6Cl_2$ and is transmitted along the interface. These results suggest that the SPP is excited at the interface between Au and $C_7H_6Cl_2$, wherein reflectance becomes close to 0. Therefore, it can be concluded that GaP is effective in detecting $C_7H_6Cl_2$.

Conclusion: In summary, we used GaP–Au contacts as SPP chemical sensors for a high-refractive-index medium for demonstrating the detection of $C_7H_6Cl_2$. The experimental reflectance measurement results in case of $C_7H_6Cl_2$ indicate that the degrees corresponding to the excitation of SPP are consistent with the simulation data. Therefore, it can be concluded that the GaP–Au contact demonstrates the excitation of SPP, and hence can be used as chemical sensors for high-refractive-index media.

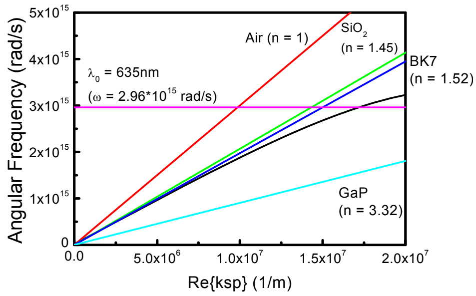

Fig. 1: Dispersion relationship between Au and $C_7H_6Cl_2$.

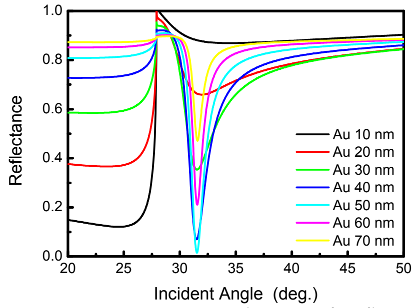

Fig. 2: RCWA simulation of reflectance depending on the incident angle.

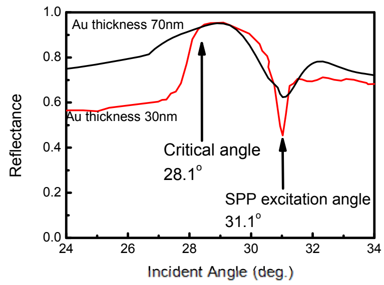

Fig. 3: Experiments of reflectance depending on the incident angle.

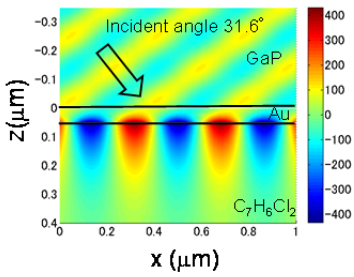

Fig. 4: Distribution of electrical field calculated by the RCWA method.

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