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Temperature detection based on surface plasmon resonance at THz wave

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Abstract. A new terahertz (THz) temperature sensor, which is based on surface plasmon resonance (SPR) by prism coupling excitation at THz frequency, is proposed. A novel prism coupling structure is designed for the temperature sensor by using unique features of thermo-optic effect for silicon at 1 THz and the high THz emission effiency of InSb. The medium thickness for the THz temperature sensor structure is analysed to get the optimal value by the finite element method, so that the sensitivity can reach optimal value. The optimal thickness of each layer is given, and the sensitivity of THz temperature sensor can reach $9.75 \times 10^{-4^\circ}/^\circ$C, and FWHM of the SPR spectrum can reach 0.073°, within the detection range of temperature, 0−80°C, and the relationship between SPR angle and temperature is obtained within the detection range of temperature.

Keywords. Temperature sensor; surface plasmon resonance; terahertz; finite element method; sensitivity.

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1. Introduction

THz waves, the electromagnetic wave with frequencies from 0.1 to 30 THz, have become a research hotspot [1–3]. As a newly developed frequency window in the electromagnetic spectrum, these waves have wide applications in physics [4], chemistry [5], biomedicine [6] and communication [7,8], especially in the field of test and detection. Temperature is an important physical parameter, and the rapid and accurate detection of ambient temperature is one of important technologies in the field of physics. There are some conventional and more mature detection methods, such as infrared detection method [9], thermistor method [10], thermocouple method [11], surface acoustic wave method [12] and fibre-optic detection method [13]. However, THz sensing research is a new and important topic because of the strong interaction between terahertz (THz) wave and matter [14]. There is no surface plasmon resonance (SPR) temperature sensor based on THz technology. The THz temperature detection by means of SPR is useful for developing a new THz temperature detection device. In this paper, a novel structure based on SPR using THz wave is designed to make a new temperature sensor that has the ability to detect ambient temperature, which has high sensitivity, high accuracy and easy operation, compared with the conventional sensing and detection method.

SPR is a physical optics resonance phenomenon. The phenomenon of total internal reflection can occur on the interface between two metal mediums. Free electron in metal film will resonate as the incident light penetrates through the interface between metal and dielectric. Then the reflection decreases greatly at a certain angle which is called the SPR angle [15–17]. The SPR angle will change with the refractive index of the medium close to the metal surface, that is, the SPR angle changes as the refractive index varies. Thus, the change of SPR angle can be determined by various physicochemical properties of the medium layer. It is showed that the SPR angle changes with the ambient temperature because of the change of refractive index with various ambient temperature, and the relationship between the SPR angle and ambient temperature is given in this paper. This can provide a theoretical preparation for making SPR temperature detecting instrument at THz frequency in the future.

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2. Theory and structure design

Silicon has obvious thermo-optic effect, and the thermo-optic coeffcient of silicon at 1 THz is 1.88×10^{-4} K^{-1}. The relationship between the temperature and the refractive index of silicon at 1 THz is obtained as follows [18]:

$$n(T) = 3.36992 + 1.88 \times 10^{-4} \cdot T, \tag{1}$$

where T is in Kelvin (K) and $n(T)$ is the refractive index of silicon in the corresponding kelvin. The relationship between temperature and refractive index is shown in figure 1.

There exists direct narrow band-gap (~ 0.18 eV) and very high electron mobility (~ 80000 cm$^2\cdot$V$^{-1}\cdot$s^{-1}) for InSb [19], which can cause high THz emission effiency [20]. The dielectric function of InSb in the THz frequency range is obtained by the Drude model as follows [21]:

$$\varepsilon(\omega) = \varepsilon_0 - \frac{\omega_p^2}{\omega^2 + i\omega\omega_\gamma}, \tag{2}$$

where $\varepsilon(\omega)$ is the dielectric function of InSb in the corresponding frequency, ε_0 is the lattice permittivity and $\varepsilon_0 = 15.6$ [22], ω_p and ω_γ are plasma frequency and scattering rate respectively, and $\omega_p = 46 \times 10^{12}$ rad/s, $\omega_\gamma = 0.3 \times 10^{12}$ rad/s [23].

A novel THz coupling structure was designed for the temperature sensor, which is composed of a silicon prism, TOPAS (a new polymer material, and is a cyclic olefin copolymer), InSb, TOPAS and air layer successively, as shown in figure 2. The incident light source of 1 THz is chosen.

The THz incident light, p-polarised light, falls on the metal layers through the prism by total reflection.

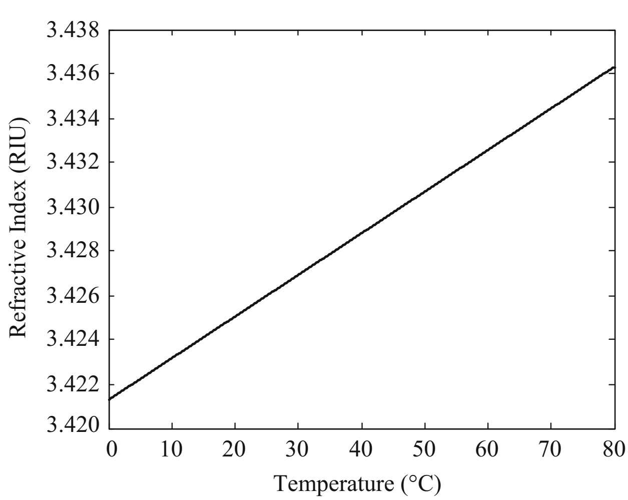

Figure 1. Relationship between temperature and refractive index.

There exists a THz evanescent wave whose amplitude is decayed exponentially normal to the interface because of the total reflection. When $k_{x0} = \mathrm{Re}(k_{sp})$, surface plasmon, at the interface of the metal and dielectric, are excited by the THz evanescent wave. The relationship between them are given as follows:

$$\varepsilon_j = n_j^2, \tag{1}$$

$$k_{sp} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_j \varepsilon_{j+1}}{\varepsilon_j + \varepsilon_{j+1}}}, \tag{2}$$

$$k_{x0} = \sqrt{\varepsilon_0}\frac{\omega}{c}\sin\theta, \tag{3}$$

where k_{x0} is the wave number vector of the incident light across the medium, k_{sp} is the wave number vector of the surface plasmon wave, $\varepsilon_j (j = 0, 1, 2, \ldots, 4)$ is the dielectric constants of each medium layer including the prism, polymer (TOPAS), InSb, polymer (TOPAS) and air respectively. $n_j (j = 0, 1, 2, \ldots, 4)$ is the refractive index correspondingly, c is the speed of light in vacuum, ω is the frequency and θ is the angle of incidence.

When the THz incident light is p-polarised, the reflection coefficient R can be given, according to the Fresnel equation and the reflectivity equation, as follows:

$$R = |r_{06}|^2 = \left|\frac{r_{01} + r_{16}\exp(2ik_{z1}d_1)}{1 + r_{01}r_{16}\exp(2ik_{z1}d_1)}\right|^2, \tag{4}$$

where

$$r_{pq} = \frac{n_p^2 k_{zq} - n_q^2 k_{zp}}{n_p^2 k_{zq} + n_q^2 k_{zp}}$$

is the reflection ratio of the strength for the electric field at the interface between the two adjacent medium and

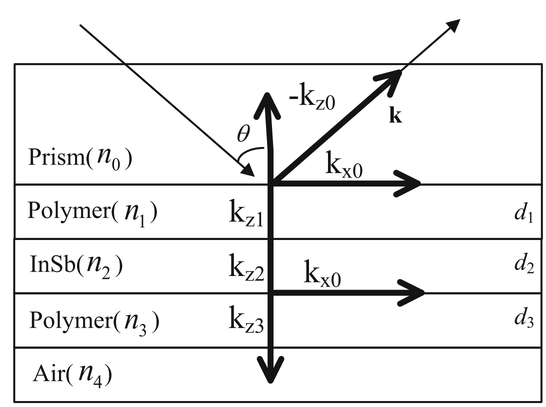

Figure 2. Structure designed for the temperature sensor.

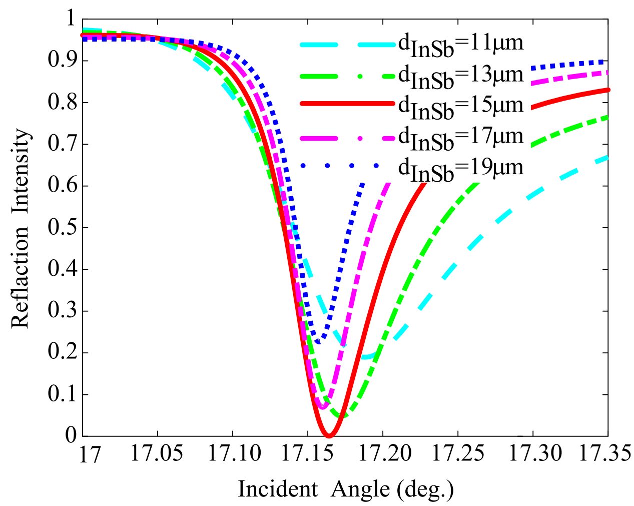

Figure 3. SPR spectrum for different thicknesses of InSb layer, $d_{\mathrm{InSb}} = 13\,\mu$m, $14\,\mu$m, $15\,\mu$m, $16\,\mu$m and $17\,\mu$m.

$$k_{zj} = \sqrt{\left(\frac{\omega}{c}\right)^2 n_j^2 - k_{x0}^2},$$
$$(p = 0, 1, \ldots, 3, q = 1, 2, \ldots, 4 \text{ and } j = 0, 1, 2 \ldots, 4).$$

3. Results and discussion

The effect of thickness of the InSb layer on SPR angle, for the temperature, $t = 30$°C, are shown in figure 3, where the thicknesses are 10 nm and 10 nm for the first polymer layer and the second polymer layer respectively. It can be seen that, the SPR peak moves towards the minimum value gradually when the thickness of the InSb layer increases from a value less than $15\,\mu$m to $15\,\mu$m, and the SPR peak moves far from the minimum value gradually when the thickness of the InSb layer increases from $15\,\mu$m to a value more than $15\,\mu$m. That is, the optimal SPR spectrum can be obtained when the thickness of InSb layer reaches $15\,\mu$m, which is suitable for other temperature range studied.

The effect of temperature on the SPR spectrum for the structure designed are shown in figure 4, where the SPR spectra for $t = 0$°C and 80°C, are given. The SPR spectrum changes because of different temperature. Concretely speaking, the SPR spectrum moves towards the lower temperature, the SPR angle shifts to the lower temperature correspondingly and decreases significantly with the increase in temperature. Thus, the thicknesses 10 nm, 15μm and 10 nm are chosen for the first polymer layer, InSb layer and second polymer layer respectively, for the structure designed. The figure of merit, SPR spectra for different temperature are shown in figure 4.

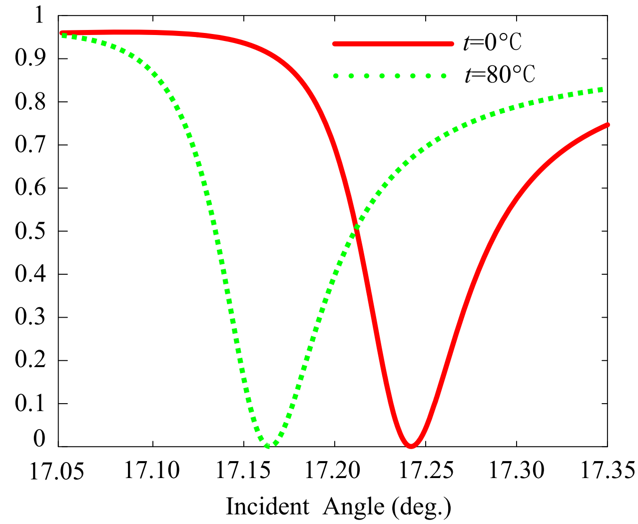

Figure 4. SPR spectra for different temperatures, $t = 0$°C and 80°C.

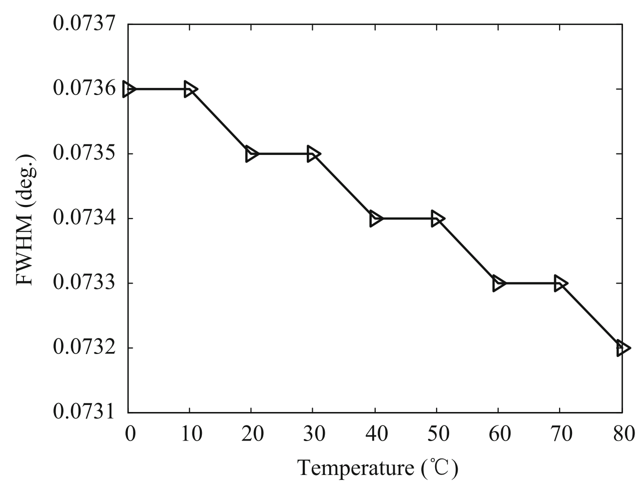

Figure 5. Relationship between FWMH of the SPR spectrum and temperature.

The full width at half maxima (FWHM) of the SPR spectrum at the temperature range 0–80°C, are given in figure 5. It is obviously found that the FWHM of the SPR spectrum changes from 0.0736° to 0.0732° as the temperature varies from 0°C to 80°C.

The intensity of interaction between light and matter is different because of the different thicknesses of the medium, leading to the change of the proposed SPR sensor sensitivity in a specific temperature range. The sensitivity of the SPR sensor is the change in SPR angle divided by the change in refractive index, and in turn the sensitivity of the SPR temperature sensor is the change in SPR angle divided by the change in temperature. The sensitivity of the SPR sensor or SPR temperature sensor can be defined as

$$S_{\mathrm{n}} = \frac{\Delta\theta_{\mathrm{SPR}}}{\Delta n}, \quad S_{\mathrm{t}} = \frac{\Delta\theta_{\mathrm{SPR}}}{\Delta t}, \tag{5}$$

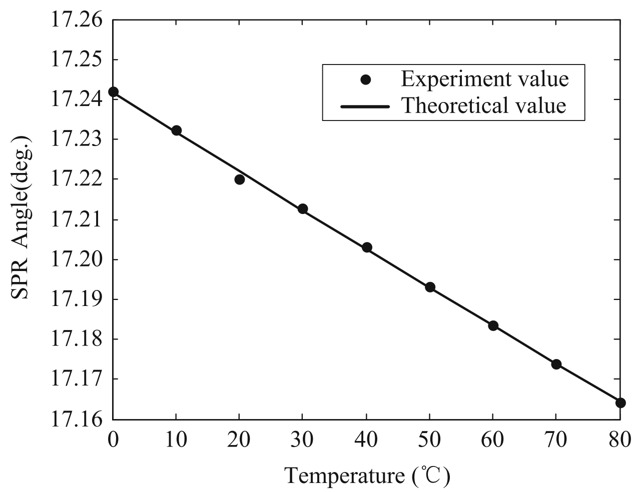

Figure 6. Relationship between SPR angle and temperature.

where $\Delta\theta_{SPR}$ is the change in resonance angle, Δn is the change in refractive index, Δt is the change in temperature, S_n and S_t are the sensitivity of the SPR sensor and SPR temperature sensor respectively.

The relationship between SPR angle and temperature is shown in figure 6. The SPR angle decreases accordingly, as the temperature increases gradually, and it reaches minimum when the temperature increases from 0°C to 80°C. In addition, there is a linear relationship between SPR angle and temperature, and the SPR angle reaches minimum when the temperature is 80°C. The SPR angle shifts significantly, ranging from 17.242° to 17.164°, within the scope of temperature, 0−80°C. Thus, the detection range of temperature sensor is 0−80°C, the shift of SPR angle is 0.078° at the detection range, and also the sensitivity reaches 5.2°/RIU in terms of refractive index change. Then the sensitivity of the SPR temperature sensor reaches $9.75 \times 10^{-4^\circ}$/°C in terms of temperature detection range.

4. Conclusion

In this paper, a novel THz temperature sensor based on SPR was designed, and the medium thickness was optimised to get good SPR spectrum and high sensitivity. The sensitivity can reach 5.2°/RIU in terms of refractive index change, and the sensitivity of THz temperature sensor reaches $9.75 \times 10^{-4^\circ}$/°C within the detection range of temperature, 0−80°C, and the relationship between SPR angle and temperature is given. Based on this, the making of a new THz temperature detection device, SPR detecting instrument at 1 THz, is theoretically possible.

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