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Non-destructive plasma frequency measurement for a semiconductor thin film using broadband surface plasmon polaritons

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ABSTRACT

Measurement of the plasma frequency of a semiconductor film using broadband surface plasmon is demonstrated in this paper. We theoretically deduce a formula about the relation between plasma frequency and characteristic surface plasmon frequency. The characteristic surface plasmon frequency can be captured from the cut-off frequency of the transmission spectra of the broadband surface plasmon, which is used to measure the plasma frequency indirectly. The plasma frequencies of an intrinsic indium antimonide with and without optical illuminance are measured with a THz time-domain spectrometer at room temperature. The experimental measured plasma frequencies fit well with theoretical and simulation results. Compared with other methods, the proposed method has a special advantage on measuring the plasma frequency for a thin semiconductor film coated on other materials.

1. Introduction

The plasma frequency is an extremely significant parameter of semiconductors [1]. In contrast with that of metals, the plasma frequency of semiconductors is easily modified by temperature fluctuation, optical illumination, carrier injection and chemical doping [2,3]. Thus even though we know the chemical formula of a semiconductor, we still cannot exactly know the plasma frequency of the semiconductor. Therefore, rapid, accurate, sensitive, non-destructive and non-contact measurements of the plasma frequency of semiconductors have recently attracted much research attention [4]. Traditional electrical measurement methods are commonly used to quantify the plasma frequency through the Hall effect [5–7]. However, the Hall effect is difficult to be applied to the surface layer of a semiconductor grown or attached on other materials such as metal or semiconductor substrates. Another widely used method is infrared reflectometry [8], which can be used to measure the plasma frequency of a thin semiconductor deposited on a substrate. Nonetheless, substrate material, sample thickness and surface roughness seriously affect the measurement accuracy. One has to calibrate before each measurement, which inevitably increases measurement complexity. In order to overcome these limitations, we propose a new method based on surface plasmon polaritons (SPPs) operating in the far-infrared and terahertz (THz) frequency range.

SPPs are known to be nonradiative in nature and exhibit strong field enhancement at the interface between two media with permittivities of opposite signs [9]. Most of the previous effort has been concentrated on investigating SPPs in the visible and near-infrared (IR) domain on metal surfaces [10]. In fact, not only metals support electron plasma oscillations, but semiconductors can also support SPPs [11,12]. Nevertheless, SPPs with visible or near-infrared frequencies cannot propagate along the surface of a semiconductor. This is because the real part of the semiconductor's permittivity is positive for SPPs with frequencies higher than the plasma frequency of the semiconductor [13]. In order to measure the plasma frequency of the semiconductor, we use broadband electro-magnetic (EM) waves with frequencies around the plasma frequency of the semiconductor to generate SPPs on the semiconductor. Since the intensities of the SPPs propagating on semiconductors are highly confined to the surface especially when the frequencies of the SPPs approach the plasma frequency of the semiconductor [14,15], the substrate beneath the semiconductor film has minimal perturbation on the measurement of the plasma frequency. This is a special merit of the

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proposed method compared with other plasma frequency measurement methods reported in previous literature [16,17].

2. Relationship between the plasma frequency and the characteristic surface plasmon frequency

We obtain the plasma frequency by measuring the characteristic surface plasmon frequency through the transmission spectra of the SPPs. Therefore, clarification of the relation between the plasma frequency of the semiconductor and the characteristic surface plasmon frequency is critical. According to the SPP dispersion relation [18], the propagation constant along the direction of a semiconductor–air interface is given by

$$k_x = \frac{\omega}{c}\sqrt{\frac{\varepsilon_{air}\varepsilon_{semi}}{\varepsilon_{air}+\varepsilon_{semi}}} \tag{1}$$

where c is the speed of light in vacuum; ω is the angular frequency of SPPs, ε_{air} is the permittivity of air, ε_{semi} is the permittivity of the semiconductor. According to the Drude model [19], the permittivity of the semiconductor is given by

$$\varepsilon_{semi} = \varepsilon_{static}\left[1 - \frac{\omega_p^2\tau^2}{1+\omega^2\tau^2} + i\frac{\omega_p^2\tau}{\omega(1+\omega^2\tau^2)}\right] \tag{2}$$

where ε_{static} is the static permittivity, τ is the average collision time of the charge carriers and ω_p is the plasma angular frequency. At large k_x or $\varepsilon_{air} \to -\varepsilon_{semi}$, $\omega \to \omega_{sp}$ (ω_{sp} represents the characteristic surface plasmon angular frequency), the product $\omega\tau \gg 1$ [20] and ε_{semi} is predominantly real, thus we get the following equation

$$\varepsilon_{air} = -\varepsilon_{semi} = -\varepsilon_{static}\left[1 - \frac{\omega_p^2}{\omega_{sp}^2}\right] \tag{3}$$

Considering the relation between the angular frequency and frequency, i.e.

$$\omega_{sp} = 2\pi f_{sp} \tag{4}$$

$$\omega_p = 2\pi f_p \tag{5}$$

We can calculate the plasma frequency of the semiconductor by substituting Eqs. (4) and (5) into Eq. (3). The plasma frequency is given by

$$f_p = f_{sp}\sqrt{\frac{\varepsilon_{static}+\varepsilon_{air}}{\varepsilon_{static}}} \tag{6}$$

Because the static permittivity ε_{static} and the permittivity of air ε_{air} in Eq. (6) are constant, only the characteristic surface plasmon frequency f_{sp} is varied with temperature fluctuation, optical illumination and carrier injection. Therefore, the application of measuring the plasma frequency f_p turns to detecting the characteristic surface plasmon frequency f_{sp}.

3. Design of the measurement setup

The characteristic surface plasmon frequency can be captured from the transmission spectra of broadband SPPs propagating along the semiconductor surface. In order to get the transmission spectra, we use a slit coupling setup, which can be used to excite broadband SPPs along the semiconductor surface then couple back to free space waves [21]. As shown in Fig. 1, we launch a p-polarized broadband wave at a slit created between a razor blade and the semiconductor surface. The broadband wave is scattered at the slit and the scattered waves comprise a continuum of both propagating and evanescent fields, which makes the excitation of SPPs possible [22]. The SPPs propagate along the semiconductor surface at directions normal to the razor blade. A second blade placed at a short distance from the first one is used to couple the SPPs back into free propagating radiation, which is then detected by a spectrometer. Considering that the temperature may affect the plasma frequency of the semiconductor during the measurement process, a thermo-electrical controller (TEC) is mounted under the semiconductor to ensure that the temperature of the semiconductor is uniform and stable.

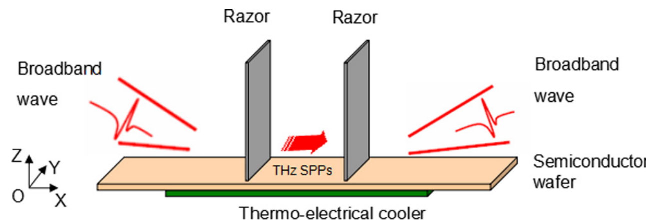

Fig. 1. Schematic of the slit coupling setup.

4. Simulation results

To demonstrate how to measure the characteristic surface plasmon frequency, we have performed a series of two-dimensional (2D) simulations with different THz SPP frequencies using the finite-element method. The modeled structure is shown in Fig. 2 and a minimum 0.48 μm mesh size is used in the simulations. We assume the underdetermined semiconductor is an intrinsic indium antimonide (InSb) semiconductor of thickness 0.45 mm with a carrier density of 1.169×10^{16} cm^{-3} at room temperature. A p-polarized THz wave is incident on the surface of the InSb wafer at an angle of 67°. The width of the slit defined by the razor blade and the semiconductor surface is 200 μm. The electric field distributions and the normalized transmission spectra of SPPs through the InSb surface are shown in Fig. 2(a) and (b). The results in Fig. 2(a) indicate that the surface plasmon components at 1.6, 1.7 and 1.8 THz can propagate through the semiconductor. In contrast, the surface plasmon components at frequencies above 1.9 THz cannot pass through the device. This is shown in Fig. 2(b), where one observes minimal transmission beyond 1.9 THz. According to the dispersion relation of SPPs, only the SPPs with frequencies below the characteristic surface plasmon frequency can propagate along the semiconductor surface. Therefore, the simulation results show that the characteristic surface plasmon frequency of intrinsic InSb is between 1.8 THz and 1.9 THz. The simulation results also indicate that the characteristic surface plasmon frequency can be obtained from the cut-off frequency of transmission spectrum if a broadband beam is used to excite the SPPs.

5. Experimental setup and results

We have done experiments to prove the feasibility of measuring the plasma frequency of a semiconductor. The underdetermined semiconductor used in the experiment is an intrinsic InSb wafer. The InSb wafer is 0.5 mm thick, with a 2 inch diameter. The frequency-dependent transmission spectra are obtained via a typical THz time-domain spectrometer (THz-TDS, EKSPLA, 0.1–5.0 THz). We show a schematic of our setup in Fig. 3. A beam of femtosecond optical pulses (100 fs, 80 MHz) emitted from a Ti:sapphire laser (Coherent, Vitesse-800-5, 800 nm) is split into two beams: generation and detection. The first generation beam is used to generate linearly polarized picosecond THz pulse by optically exciting a photoconductive antenna using low-temperature grown gallium arsenide (LT-GaAs). The thickness of the GaAs substrate is 400 μm and the antenna contacts are formed using Ti/Au metallization. The generated THz radiation is partially coupled into THz SPPs propagating along the surface of the InSb wafer for plasma frequency measurement. A TEC is mounted under the InSb wafer to ensure that the temperature of the wafer is 300 K. The second beam gates the photoconductive antenna, which detects the THz field coupled out from the THz SPPs. By varying the time delay between the two pulse trains, the THz pulse amplitude can be detected as a function

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