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THz Wave Modulator Based on the Decay of THz Surface Plasmon along an Intrinsic InSb Surface

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Abstract. THz surface plasmon are decayed exponentially when propagating along the surface of a semiconductor. A metal razor blade is used to couple THz surface plasmon to THz waves at different position on the surface of an indium antimonide wafer. Thus the intensity of the output THz wave is modulated.

1. Introduction

Terahertz (THz) waves are electromagnetic radiation in the frequency range of 0.1 to 10 THz. Terahertz frequencies are attractive for the communication industry because this frequency band is currently unallocated by the Federal Communications Commission [1]. THz waves have greater bandwidth than microwave and suffer less Rayleigh scattering compared with infrared radiation. However, several obvious shortcomings of traditional THz modulators have prevented further development of THz based communications, for example, operation at cryogenic temperatures [2]; achievable modulation depth of only a few percent of the signal intensity [3]; difficulty in realizing high frequency modulation [4]. In view of the difficulty of controlling a THz wave, we turn to investigating how to control surface plasmon polaritons (SPPs) with THz frequencies because THz SPPs and THz wave can couple to each other with two razor blades.

SPPs have been the subject of intense research in recent years [5]. Most of the effort has been concentrated on investigating SPPs in the visible and near-infrared domain on metal surfaces [6]. However, not only metals support electron plasma oscillations, but semiconductors can also support SPPs. Intrinsic indium antimonide (InSb) with carrier densities of $1 \times 10^{16}$ cm$^{-3}$ and plasma frequency of 1.9 THz at 300 K is an ideal material for THz modulation devices because it offers the possibility of ultrafast active modulation with extremely small fluctuations of a razor blade position. Compared with traditional optical switching THz SPP devices that required grating with complex structure [7], the new device reported in this paper only need a flat InSb wafer and two parallel razor blades with a modulated distance, therefore the whole setup is quite simple.
2. Design of the Modulator

Figure 1. Schematic of the design.
Figure 1 shows the schematic of the design. Here free-space THz radiation is scattered at the aperture defined by a razor blade and the surface of the semiconductor coupling to SPPs if the frequency of the THz SPPs is smaller than the plasma frequency of the InSb semiconductor [8]. After propagating in the surface of the InSb semiconductor, the SPPs are coupled back to free-space THz radiation by another parallel razor blade. THz modulation is realized by changing the distance of the two razor blades.

3. Principles of Operation

THz surface plasmon are decayed exponentially when propagating at the interface of two media with opposite signs of permittivity. According to the Drude model [9], the permittivity of a semiconductor is related to the plasma angular frequency which is given by

\[
\varepsilon = \varepsilon_e^0 + \frac{\omega_p^2}{1 + \frac{\omega^2}{\omega_p^2}} + i \frac{\omega_p \tau}{\omega(1 + \omega^2 \tau^2)}
\]

(1)

where \( \varepsilon_{\text{static}} \) is the static permittivity; \( \tau \) is the average collision time of the charge carriers; \( \omega \) is the angular frequency of THz SPPs; \( \omega_p \) is the plasma angular frequency, which can be expressed as

\[
\omega_p = 2\pi f_p = \sqrt{\frac{Ne^2}{\varepsilon_0 \varepsilon_{\text{static}} m^*}}
\]

(2)

where \( f_p \) is the plasma frequency; \( N \) is the free carrier density; \( e \) is the fundamental charge; \( \varepsilon_0 \) is the vacuum permittivity and \( m^* \) is the carrier effective mass.

Thus, the propagation length of THz SPPs along the direction of a semiconductor–air can be written as [10]

\[
\delta_p = \frac{c}{\omega_p} \left( \frac{1 + \varepsilon}{\varepsilon} \right)^{1/2} \frac{e^2}{\varepsilon'}
\]

(3)

Therefore, we can modulate the intensity of the output THz wave by putting two razor blades above the surface of the semiconductor with a modulated separation distance. Figure 2 shows the propagation lengths of THz SPPs on the surface of a flat intrinsic InSb wafer and a gold flat film. Compared with the propagation lengths on the gold film, that on the semiconductor are much short. Therefore, we can modulate the THz SPPs with a small distance fluctuation of razor blades on the semiconductor, which may lead to high modulation frequency.
4. Simulation Results

In order to demonstrate the propagation properties of THz SPPs in the surface of an intrinsic InSb wafer as shown in figure 1, we have performed a series of two-dimensional simulations with varying razor blade distances by using a finite element software. The modeled structure is shown in figure 1 and a minimum 0.32 μm mesh size is used in the simulations. We assume the SPP waveguide to be the intrinsic InSb semiconductor of thickness 0.45 mm. A p-polarized THz wave is incident at an angle of 63°. For simplicity, the THz wave used in the simulation is a monochromatic wave with a frequency of 0.5 THz because the coupled THz SPPs with this frequency have the merits of long propagation lengths and high field confinement to the surface. The size of the gap, defined as the distance between the two razor blades and the semiconductor surface, is 150 μm and the distance between the two razor blades is 3 mm, 4 mm and 5 mm respectively. The electric field distributions shown in figure 3 indicate that the intensity of the surface plasmon and its output THz wave are gradually weak when the distance between the two razor blades is increased from 3 mm to 5 mm. Our simulation results clearly show that for a THz wave with a frequency of 0.5 THz the device may act as a modulator by changing the distance of the two razor around 4 mm with 1 mm variation.

Figure 2. Relation between the frequency and propagation length of THz SPPs propagating on a InSb wafer and on a gold film.

Figure 3. Spatial distribution of the electric field amplitudes of THz SPP components with frequencies of 0.5 THz on the surfaces of intrinsic InSb semiconductors.
5. Experimental Results

We can also modulate a broadband THz wave. We demonstrate it by measuring the transmission power spectra with a free-space THz time-domain spectroscopy (THz-TDS, EKSPLA) system [11-12]. The experimental setup is shown in figure 4. In the figure, a train of ultra short optical pulses (120 fs, 800 nm) from a Ti:Sapphire laser (Coherent, Chameleon) is split into two beams. One of these beams is used to optically generate coherent and linearly polarized THz radiation from a low temperature grown gallium arsenide (LT-GaAs) surface field emitter. The thickness of GaAs substrate is 400 μm and the antenna is formed using Ti/Au metallization. The generated THz radiation is coupled into THz SPPs propagating in the surface of an InSb wafer for modulation. The other beam gates a 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 of time with subpicosecond resolution as shown in figure 5 [13]. The measured THz pulses are Fourier transformed to obtain the transmission power spectra as shown in figure 6. The InSb wafer used in the experiment is 0.5 mm thick with 2 inches diameter. The size of the razor apertures and the incident angle of THz radiation are the same as those used in simulations.

The spectra in figure 5 and figure 6 show that the amplitude of the output THz wave is decreased by increasing the separation of the two razor blades, which indicates that the setup can act as a THz modulator by shifting the position of the razor blade on an intrinsic InSb wafer. The experimental results fit well with the experimental results. We also note that the transmission spectra fluctuate at some frequencies in figure 6, which is estimated to be due to water vapor absorption [14-15] and low signal to noise ratio.
Figure 5. Time domain spectra of the output THz wave for different razor blade separation on an intrinsic InSb wafer.

Figure 6. Frequency domain spectra of the output THz wave for different razor blade separation on an intrinsic InSb wafer.

6. Conclusion
In summary, we have proposed a THz wave modulator with a flat InSb wafer and two parallel razor blades. The modulation is realized by changing the distance of the two razor blades. Compared with conventional modulators, this method of manufacturing is simpler and the modulation bandwidth is wider.

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References
[1] http://www.ntia.doc.gov/osmhome/allochrt.pdf
[2] R. Kersting, G. Strasser, K. Unterrainer 2000 Terahertz phase modulator Electron. Lett. 36, 1156–8
[3] T. Kleine-Ostmann, P. Dawson, K. Pierz, G. Hein and M. Koch 2004 Room-temperature operation of an electrically driven terahertz modulator Appl. Phys. Lett. 84 3555–7
[4] H. T. Chen, W. J. Padilla, J. M. O. Zide, A. C. Gossard, A. J. Taylor and R. D. Averitt 2006 Active terahertz metamaterial devices Nature 444 597–600
[5] M. S. Tame et al 2013 Quantum plasmonics Nat. Phys. 9 329–40
[6] T. Yang and H. P. Ho 2009 Computational investigation of nanohole array-based SPR sensing using phase shift Opt. Express 17 11205–16
[7] J. A. Sánchez-Gil and J. G. Rivas 2006 Thermal switching of the scattering coefficients of terahertz surface plasmon polaritons impinging on a finite array of subwavelength grooves on semiconductor surfaces Phys. Rev. B 73 205410
[8] C. Janke, J. Go´mez Rivas, C. Schotsch, L. Beckmann, P. Haring Bolivar, and H. Kurz 2004 Optimization of enhanced terahertz transmission through arrays of subwavelength apertures Phys. Rev. B 69 1324–32
[9] M. van Exter and D. Grischkowski 1990 Optical and electronic properties of doped silicon from 0.1 to 2 THz Appl. Phys. Lett. 56 1694–6
[10] H. Raether 1988 Surface Plasmons on Smooth and Rough Surfaces and on Gratings (Berlin: Springer) chapter 2
[11] D.R. Grischkovskiy, S. Keiding, M. van Exter, and C. Fattinger 1990 Far-infrared time-domain spectroscopy with terahertz beams of dielectrics and semiconductors J. Opt. Soc. Am. B 7 2006-15
[12] J. G. Rivas et al 2004 Time-domain measurements of surface plasmon polaritons in the terahertz frequency range Phys. Rev. B 69 1124–33
[13] K. Reimann 2007 Table-top sources of ultrashort THz pulses Rep. Prog. Phys. 70 1597–632
[14] W. Shi, and Y. J. Ding 2004 Direct measurement of resonant frequencies for H/sub2/O in the range of 0.2-4.2 THz by frequency-tuning monochromatic THz source Lasers and Electro-Optics 1 3
[15] D. M. Slocum, E. J. Slingerland, R. H. Giles and T. M. Goyette 2003 Atmospheric absorption of terahertz radiation and water vapor continuum effects J. Quant. Spectrosc. Radiat. Transfer 127 49–63