Optics Communications 359 (2016) 349–352

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Terahertz modulation using TIPS-pentacene thin films deposited on patterned silicon substrates

Jung-Min Park [a], Ik-Bu Sohn [b], Chul Kang [b], Chul-Sik Kee [b], In-Wook Hwang [b], Hyung Keun Yoo [b], Joong Wook Lee [a,*]

[a] Department of Physics and Optoelectronics Convergence Research Center, Chonnam National University, Gwangju 500-757, Republic of Korea
[b] Advanced Photonics Research Institute, GIST, Gwangju 500-712, Republic of Korea

ARTICLE INFO

Article history:
Received 3 August 2015
Received in revised form
25 September 2015
Accepted 1 October 2015

Keywords:
Laser spectroscopy
THz spectroscopy
Organic materials
Modulation

ABSTRACT

We demonstrate the characteristics of terahertz (THz) wave modulation by 6,13-bis(triisopropylsilylethynyl) pentacene (TIPS pentacene) thin films deposited on silicon substrates patterned with one-dimensional periodic multi-channels. The polarization independence of the THz wave modulation in the hybrid structures with one-dimensional channels indicates that the rapid in-plane diffusion of the carriers injected into the TIPS pentacene thin films plays an important role in the high modulation of THz waves. Understanding the mechanisms of THz modulation is important for optimizing the performance of THz devices based on organic/inorganic hybrid structures.

1. Introduction

Terahertz (THz) technologies have attracted much attention for various applications, such as high-speed communications, spectroscopy, and sensing/imaging systems [1–5]. The realization of active THz devices such as THz modulators is necessary to improve applications based on THz technologies. Many researchers have demonstrated the possibility of active control of the transmission, reflection, spatial position, polarization, and phase of THz waves, and various materials and structures have been employed to achieve active THz modulation with high modulation efficiency [6–13].

Recently, our group and others reported that active broadband THz wave modulators can be realized based on organic/inorganic hybrid structures, and high modulation efficiency can be achieved by the selection of appropriate organic materials and their structural variations [14–18]. The modulation technique based on organic/inorganic hybrid structures provides several advantages such as high modulation efficiency, extreme broadband modulation, and easy fabrication, comparing with other techniques based on metamaterials [6–10], plasmonic structures [11,12], and semiconductor multilayer structures [13]. In order to take advantage of the technique in practice, the characteristics of THz wave modulation should be investigated for a variety of structural conditions and the diffusion properties of the photo-excited carriers injected into the organic thin film should be also studied.

In this paper, we present the characteristics of THz modulation by organic/inorganic hybrid structures that consist of a 6,13-bis (triisopropylsilylethynyl) pentacene (TIPS pentacene) film and a silicon (Si) substrate. The TIPS pentacene thin film was deposited on the Si substrate patterned with one-dimensional periodic multi-channels. We carried out polarization-dependent transmission measurements using a THz time-domain spectroscopy method and obtained the modulation efficiencies of THz transmission. The results demonstrate polarization-independent modulation efficiency, which means that the injected carriers from the patterned Si substrate to the TIPS pentacene thin films undergo rapid in-plane diffusion. These results are important for developing versatile THz devices and for optimizing their performance.

2. Experimental setup and sample fabrication

Fig. 1(a) shows the schematic diagram of the designed structure. TIPS pentacene molecules were deposited on a high-resistivity silicon (Si) substrate patterned with one-dimensional U-shaped channels. First, three types of patterned Si substrates were fabricated by femtosecond laser machining [19], a flat Si substrate without any pattern (Sample A), a Si substrate with 10-μm-deep channels (Sample B), and a Si substrate with 30-μm-deep channels (Sample C), as shown in Fig. 1(b). TIPS pentacene,

* Corresponding author.
E-mail addresses: hkyoo@gist.ac.kr (H. Keun Yoo), leejujc@jnu.ac.kr (J. Wook Lee).

http://dx.doi.org/10.1016/j.optcom.2015.10.008
0030-4018/

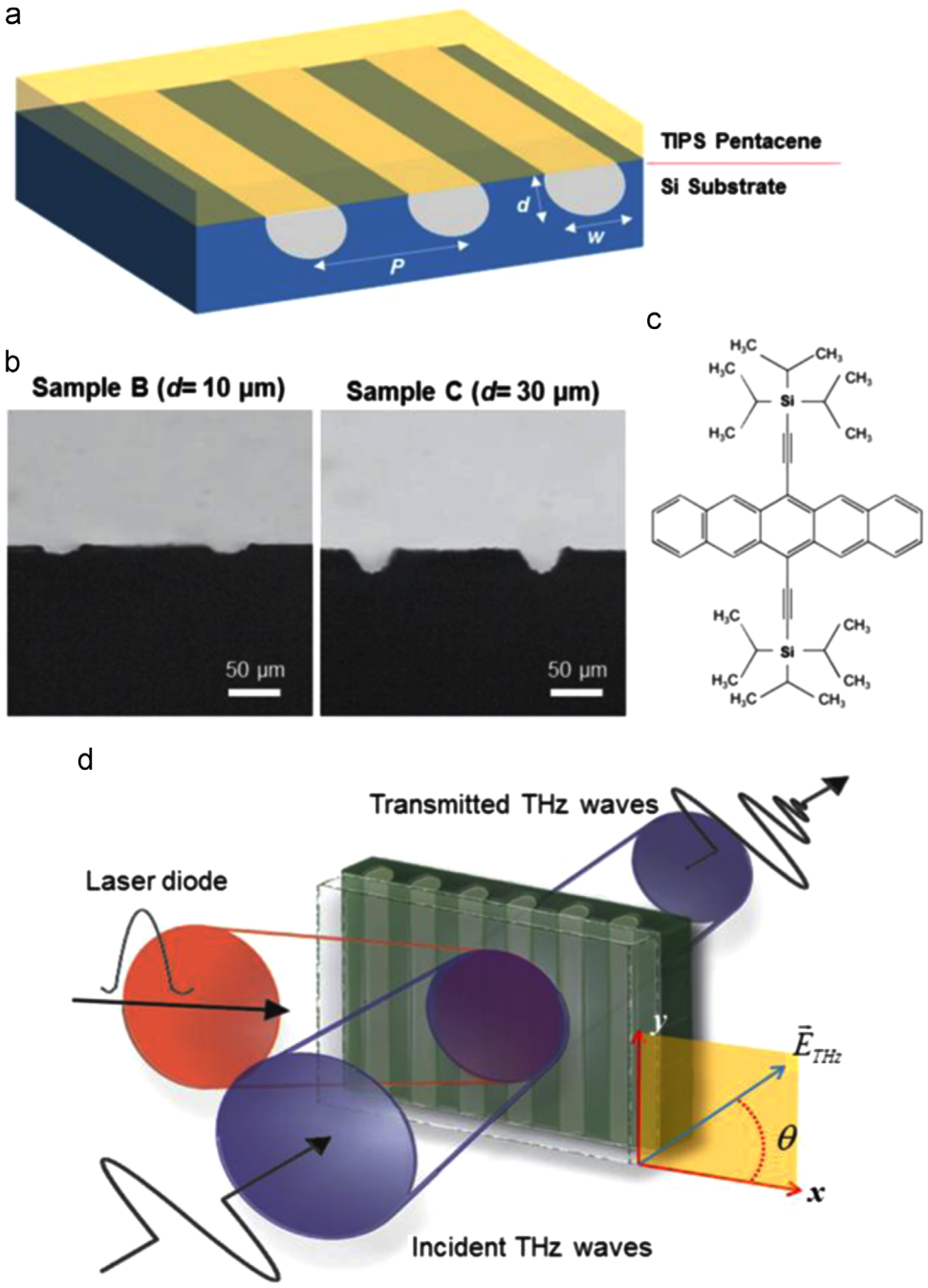

Fig. 1. (a) Three-dimensional schematic of the Si/TIPS pentacene hybrid structures. The dimensions are as follows: $p=150$ μm, $w=40$ μm, and $d=0$, 10 and 30 μm. (b) Microscopy images of Si substrates with U-shaped channels of $d=10$ μm (Sample B) and $d=30$ μm (Sample C). (c) Molecular structure of TIPS pentacene. (d) Schematic view of THz transmission through the samples. The incident THz pulses and the optical beam for photo-excitation are incident onto the same area of the sample surface normally and obliquely, respectively.

which is a high-performance soluble organic semiconductor used in optical devices and flexible electronics (Fig. 1(c)) was purchased from Sigma-Aldrich (product number: 716006). The molecules were deposited on top of the Si substrates by drop casting. After dropping 50 μl of TIPS pentacene solution (2 mg/ml) onto the Si substrate, the molecules were covered with a glass lid and heated for 5 min on a hotplate at 50 °C.

The THz modulation characteristics were measured in a transmission THz time-domain spectroscopy system [20–22]. THz pulses were generated using a (100) p-type InAs crystal, generating the photo-Dember field due to its high electron mobility, collimated by parabolic mirrors, focused with a THz lens and detected with a photoconductive antenna. The THz pulses were transmitted through a 3-mm-diameter pinhole onto the samples under photo-excitation by a cw diode laser. An optical beam with a wavelength of 785 nm was used as the light source for photo-excitation. It was incident with an oblique angle of 45° and a power of 80 mW and excited the area of the sample surface sectioned by the 3-mm-diameter pinhole. As shown in Fig. 1(d), the angle θ was counted off from the x-axis on the surface plane of the samples and indicates the polarization direction of the incident THz waves. At $\theta=0°$, the direction of the U-shaped channels in the Si/TIPS pentacene layers was perpendicular to the electric field of the polarized, incident THz waves. Polarization dependent transmission