Wide-band enhanced terahertz wave modulation by a graphene-on-silicon modulator

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Abstract

We report experimental results on efficient all-optical modulation of terahertz waves over a wide band from 0.2 to 1.5 THz with a modulation depth of up to 99% by means of a graphene-on-silicon (GOS) modulator. We observed that the sensitivity of the GOS modulator to the incident power of the modulating laser beam was significantly enhanced in comparison with a basic silicon modulator. We developed an analytic model that describes the quasi-fermi levels at the interface between silicon and graphene and allowed us to qualitatively understand the modulation enhancement of the GOS modulator. The fabrication of metamaterial structures on top of GOS promises the development of metamaterials with adaptive electromagnetic properties.

1. Introduction

Graphene currently awakens great interest of researchers in the various disciplines of optics and electromagnetics. It is notable that a rising amount of publications describes the suitability of graphene for applications in optics and terahertz (THz) physics. Especially the possibility to control the surface conductivity of graphene by electronic means could be exploited for a variety of applications. For example, voltage driven modulators were suggested for use in the optical as well as the THz regime and tunable metamaterials fabricated of graphene micro-ribbon arrays were successfully demonstrated [1, 2, 3].

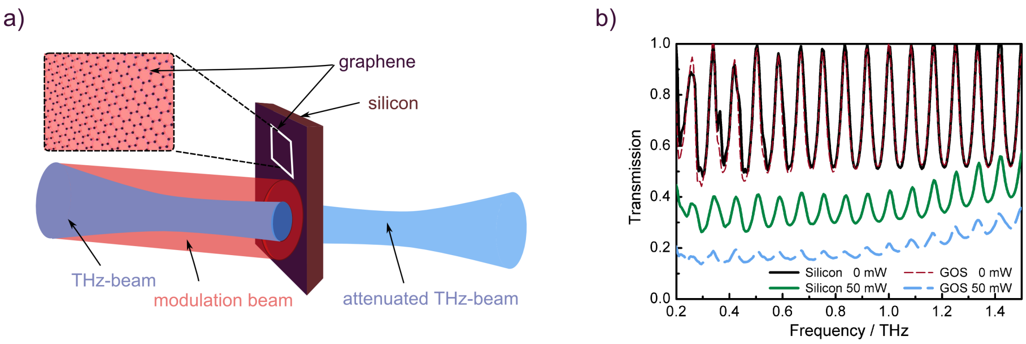

Fig. 1: (a) Schematic of the set-up for the modulation experiment. (b) Transmission spectra of the Si and GOS modulator without illumination and with an illumination power of P = 50 mW.

Another ambiguous work following this idea recently proposed the implementation of transformation-optical media with a thickness of one single atomic layer [4]. Here, we demonstrate spectrally wide-band all-optical modulation of terahertz waves from 0.2 to 1.5 THz by means of a graphene-on-silicon modulator. We experimentally evidence that graphene on top of silicon significantly enhances the sensitivity of the modulator to the external control radiation in comparison with pure silicon (Si). We corroborate these results by an analytic model that qualitatively describes the enhancement effect. GOS is a promising substrate for the implementation of optically tunable metamaterials [5].

2. Experimental investigation of the modulator

Fig. 1(a) shows a schematic of the set-up for the modulation experiment. For the fabrication of the GOS modulator, we transferred commercially available graphene from a copper foil to a high-resistivity silicon (Si) wafer by use of a thermal release tape. By Raman spectroscopy, we verified the existence of a graphene layer on the Si substrate. We observed prevalent regions with single layer graphene but also isles with two and more layers. In the experiment, we spatially overlapped the optical modulation beam with the THz beam and measured the spectral THz transmission dependent on the modulation power by time-domain spectroscopy. As a modulation source we employed a pulsed infrared laser (wavelength $\lambda = 780\ \mathrm{nm}$, pulse duration $\tau \approx 100\ \mathrm{fs}$) with a repetition rate $\tau_r = 12.5\ \mathrm{ns}$ which was several orders of magnitude shorter than the charge carrier lifetime $\tau \geq 1\ \mu\mathrm{s}$. Consequently, only the time averaged power of the beam rather than the pulse energy determined the modulation depth, independent of the time delay between THz and modulation pulse.

Figure 1(b) compares the spectral THz transmission of a Si modulator and a GOS modulator without optical modulation beam and for a modulation power of 50 mW. In all cases, the transmission spectra are frequency-modulated mainly due to etalon effects in the Si substrate. When the modulation beam is turned off, the transmission for both the Si and GOS modulator is close to unity. Upon turn on of the modulation beam with a power of 50 mW the transmission through the Si modulator decreases due to the excitation of electron-hole pairs at the Si surface which increases the conductivity and lowers the transmission. A similar behavior can be expected for the GOS modulator, but as can be seen in Fig. 1(b), the GOS transmission is about half the transmission of the Si modulator. An inspection of the modulation depth in Fig. 2(b) shows that GOS offers a higher modulation depth than Si up to an illumination power of 400 mW before the enhancement effect saturates.

3. Semi-analytic model of modulation

For the description of optical modulation in pure Si we used a semi-analytic model that determines the conductivity change based on quasi-fermi levels for electrons and holes in the semiconductor. We considered the semiconductor in quasi-thermal equilibrium and expressed the conductivity by $\sigma = q\mu_n n + q\mu_p p$ with elementary charge q, electron/hole mobilities μ_n and μ_p and electron/hole densities n and p. The electron and hole densities can be calculated by $n = N_c exp(-\frac{E_g - \Delta\mu}{2k_B T})$ and $p = N_V exp(-\frac{E_g - \Delta\mu}{2k_B T})$ with band gap $E_g = E_C - E_V$, effective conduction/valence band density of states N_C and N_V and the separation energy of the quasi-fermi levels for electrons and holes $\Delta\mu = E_{Fe} - E_{Fh}$ as depicted in Fig. 2(a). With respect to the GOS modulator, only a small fraction of 2.3% of radiation is absorbed in the graphene layer and thus almost all free charge carriers are generated in the silicon [1]. In consequence, a charge density gradient is induced near the interface between Si and graphene. The density gradient tends to be balanced by the diffusion currents $J_n = \mu_n n \nabla E_{F_n}$ for electrons and $J_p = \mu_p p \nabla E_{F_p}$ for holes until the separation energy $\Delta\mu$ of the quasi-fermi-levels of graphene and silicon at the interface is approximately equal to the separation energy in pure silicon. Due to the conical band structure of graphene, the density of states attainable by intraband transitions increases with the separation energy and thus the graphene conducitvity increases. This can be calculated following ref. [6]. We derived the conductivity of the modulated silicon from simulations of a two-layer system comprised of a thin sili-

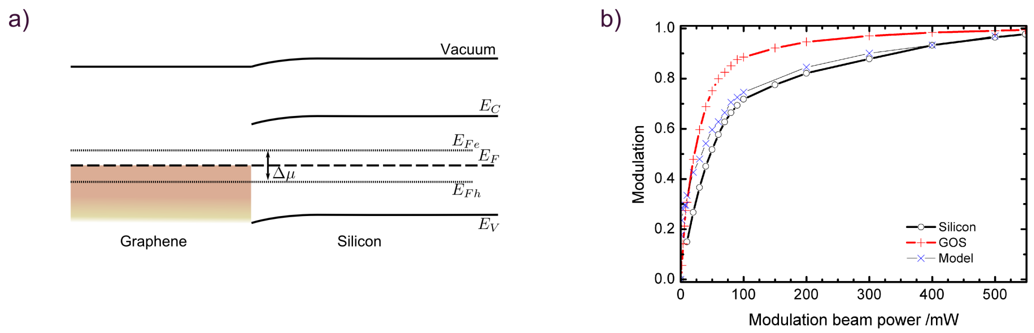

Fig. 2: a) Bandscheme of the silicon-graphene heterojunction. b) Measured dependence of the modulation depth on the modulation power for silicon and GOS. The modulation depth was averaged over a frequency band from 0.2-1.0 THz. The semi-analytic results for GOS are in good agreement.

con layer with a constant conductivity σ, which corresponds to the modulation beam penetration range, and a loss-free silicon layer. Subsequently, we fitted the conductivity for different modulation powers to match the numerically calculated spectral transmission with the experimental values and determined the separation energy $\Delta\mu$ of the quasi-fermi levels in silicon. Based on this quantity, we determined the conductivity of the graphene layer following [6] and included this value in the numerical calculations. As a result we obtained the modulation depth of the GOS modulator in dependence on the modulation power. As an example, Fig. 2(b) shows this dependence integrated over a range from 0.2 to 1.0 THz. As can be seen, the calculated spectral transmission is in good agreement with the measured GOS transmission up to a modulation beam power of $P = 30$ mW. With increasing power the model curve approaches the transmission characteristics of pure silicon. This deviation probably originates from thermal doping effects which were neglected in the model.

4. Conclusion

We experimentally demonstrated spectrally wide-band all-optical modulation of terahertz waves by use of a graphene-on-silicon (GOS) modulator. We achieved a modulation depth of up to 99% over a frequency range from 0.2 to 1.5 THz. We showed by experimental and semi-analytic means that the modulation depth of GOS is enhanced in comparison with a pure silicon modulator. Wideband modulation of terahertz waves is of uttermost interest for terahertz communication. In particular, graphene-on-silicon substrates seem promising for the implementation of optically tunable terahertz metamaterials.

References

[1] M. Liu, X. Yin, E. Ulin-Avila, B. Geng, T. Zentgraf, L. Ju, F. Wang, and X. Zhang, A graphene-based broadband optical modulator, *Nature* vol. 474, p. 64, 2011.
[2] B. Sensale-Rodriguez, T. Fang, R. Yan, M. M. Kelly, D. Jena, L. Liu, and H. G. Xing, Unique prospects for graphene-based terahertz modulators, *Applied Physics Letters*, vol. 99, p. 113104, 2011.
[3] L. Ju, B. Geng, J. Horng, C. Girit, M. Martin, Z. Hao, H. A. Bechtel, X. Liang, A. Zettl, Y. R. Shen, and F. Wang, Graphene plasmonics for tunable terahertz metamaterials, *Nature Nanotechnology*, vol. 6, p. 630, 2011.
[4] A. Vakil and N. Engheta, Transformation optics using graphene, *Science*, vol. 332, p. 1291, 2011.
[5] H.-T. Chen, J. F. O'Hara, A. K. Azad, A. J. Taylor, R. D. Averitt, D. B. Shrekenhamer, and W. J. Padilla, Experimental demonstration of frequency-agile terahertz metamaterials, *Nature Photonics*, vol. 2, p. 295, 2008.
[6] V. Ryzhii, M. Ryzhii, and T. Otsuji, Negative dynamic conductivity of graphene with optical pumping, *Journal of Applied Physics*, vol. 101, p. 083114, 2007.