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Graphene photodetector integrated on an optical waveguide

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Abstract. In this paper we report on our progress on fabrication of graphene-based photodetectors integrated on an optical waveguide. Graphene is a unique material for detecting radiation due to its record low electron heat capacity and weak electron-phonon coupling. The obtained experimental data can be used to optimize modern graphene photodetectors and develop new ones.

Keywords: graphene, photodetectors, waveguides

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Графеновый фотодетектор, интегрированный на оптический волновод

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Аннотация. В этой статье мы описываем наши последние достижения в создании фотодетекторов на основе графена, интегрированных на оптический волновод. Графен является уникальным материалом для детектирования излучения благодаря своей рекордно низкой электронной теплоемкости и слабой электрон-фононной связи. Полученные экспериментальные данные могут быть использованы для оптимизации современных графеновых фотоприемников и разработки новых.

Ключевые слова: графен, фотодетекторы, оптические волноводы

Финансирование: Исследование проводилось при поддержке проекта РНФ № 23-72-00014 (измерение полосы пропускания) и гранта Программы «Научный фонд Национального исследовательского университета «Высшая школа экономики» (НИУ ВШЭ) № 24-00-035 «Фотодетекторы для фотонных интегральных» (измерение чувствительности).

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Introduction

The rapid advancement of technology has led to an exponential increase in information consumption, necessitating the development of efficient detection systems. The quest for fast and cost-effective detectors has been a longstanding priority in the field. While several photodetector types are currently available, each presents distinct limitations [1–4].

The integration of graphene-based photodetectors with optical waveguides represents a promising solution for high-speed optoelectronic applications [5]. Graphene's exceptional optoelectronic properties, including broadband absorption and high carrier mobility [6], enable the development of compact, high-throughput photodetectors on integrated photonic platforms. Recent research has demonstrated waveguide-coupled graphene photodetectors with bandwidths exceeding 100 GHz and sensitivity comparable to traditional photodiodes [7].

This study focuses on the fabrication of a 1550 nm wavelength photodetector. Special attention is devoted to device architecture, performance characteristics, and challenges related to achieving high sensitivity and speed. The combination of graphene with optical waveguides enhances light-matter interaction while maintaining compatibility with existing photonic platforms. This paper explores the design and operation principles of graphene-based photodetectors integrated on optical waveguides, along with future prospects.

Device fabrication and characterization

A silicon substrate with a 450 nm thick silicon nitride upper layer served as the foundation for waveguide structures. Electron beam lithography utilizing a negative electron-beam resist was employed to fabricate the waveguides. To create the final structure, the silicon nitride is then chemically etched in CHF_3 plasma. Our devices are equipped with focusing gratings couplers for coupling light into the chip. The technology for manufacturing waveguides, as well as focusing gratings couplers is described in detail in [8]. Following waveguide creation, graphene channel fabrication commenced. Graphene was synthesized via chemical vapor deposition (CVD) and transferred onto the silicon substrate [9]. The transferred graphene was a single layer, as confirmed by Raman spectroscopy. Positive electron beam lithography and plasma chemical etching in O_2 were used to form graphene channel. Formation of contact electrodes to graphene required the application of positive electron beam lithography and electron beam evaporation of V-Au contacts. The contact electrodes are located at different distances L_1 = 700 nm and L_2 = 300 nm from the waveguide to create an asymmetric structure. This asymmetry results in a photovoltage signal due to a combination of thermoelectric and photovoltaic effects at zero bias [10]. Fig. 1 shows optical image of fabricated device (Fig. 1, *a*) as well schematical representation of device cross section (Fig. 1, *b*).

Before the photoresponse measurements, we measured the transmission spectrum of the fabricated waveguides. The total input and output losses were about 30 dB and were then taken into account to calculate the internal responsivity of the photodetector. Next, we measure photoresponse of fabricated devices. The modulated radiation from a single-mode, continuous-wave laser operating at 1550 nm was directed through the polarization controller via the optical fiber

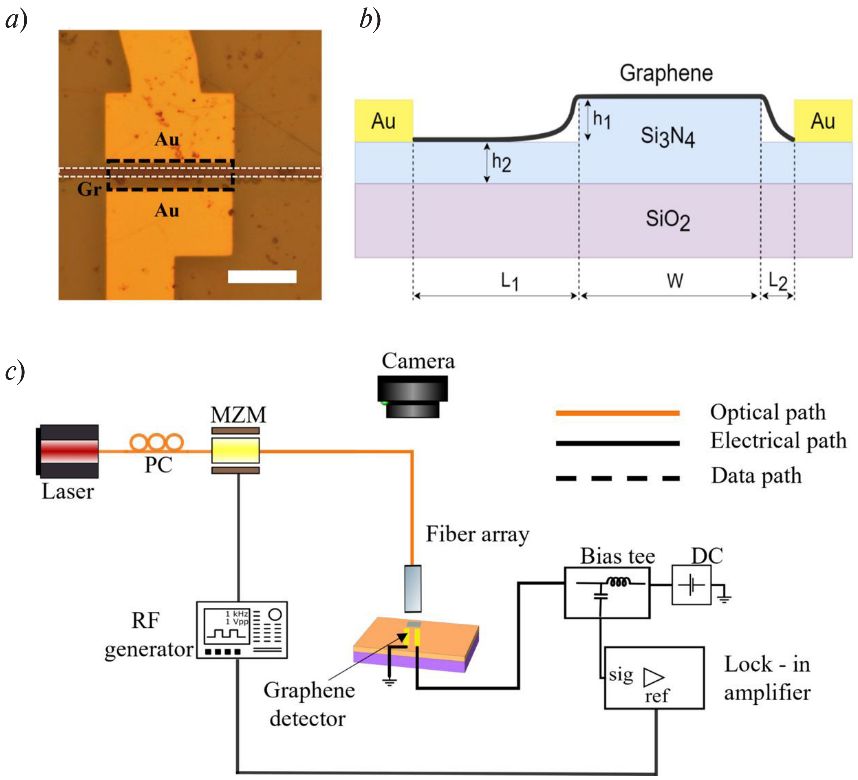

Fig. 1. Optical photograph of a graphene detector integrated onto a waveguide with gold contacts, black dashed rectangle indicates the graphene region, and the white dashed rectangle denotes the waveguide, scale bar: 10 μm (*a*); cross-sectional schematic of the graphene detector integrated onto the waveguide, where *w* represents the waveguide width, L_1=700 nm and L_2 =300 nm denote the distances from the waveguide to each gold contact, h_1 = 225 nm is the waveguide height, and h_2 = 225 nm is the thickness of the Si_3N_4 layer (*b*); schematic of the sensitivity measurement setup for the graphene detector integrated onto the waveguide (*c*), sample is placed on a probe station connected to a fiber array and electrical contacts for signal readout, laser radiation is directed through a polarization controller (PC) to the fiber array, the modulating signal is generated by a radio-frequency (RF) generator and synchronized with a lock-in amplifier. DC bias is applied via a bias tee

to the input of the optical chip (Fig. 1, *c*). The laser light was coupled into and out of the planar Si_3N_4 waveguide using focusing grating couplers. The input optical power was 1 mW, and the total input and output coupling losses were about 30 dB, which were taken into account to calculate the internal responsivity of the photodetector. The radiation was detected due to the absorption of the evanescent mode by graphene, which exited the waveguide. The measured electrical signal was fed through the bias adapter to the lock-in amplifier. The bias adapter was used to measure the photovoltage signal from the bias current. The internal responsivity of the photodetector was determined as the ratio of the photovoltage to the power absorbed by graphene and was 0.1 V/W. Given the measured graphene channel resistance of approximately 1 kΩ, this corresponds to a current responsivity of about 0.1 mA/W.

The primary mechanism for detecting radiation in our photodetector is the photothermoelectric effect in graphene [11, 12], which arises from the ununiform heating of graphene electrons due to its asymmetric location on the waveguide. In this case, the intrinsic response time of the photodetector is determined by the energy relaxation time of hot electrons [3]. At room temperature, the primary energy relaxation mechanism is the interaction of electrons with acoustic phonons [13]. The intrinsic response time is determined by the electron-phonon time. This time is independent of the excitation radiation frequency at the same power level. Therefore, to evaluate the potential of our graphene for fast detection, we used a standard heterodyne detection method at sub-THz frequencies.

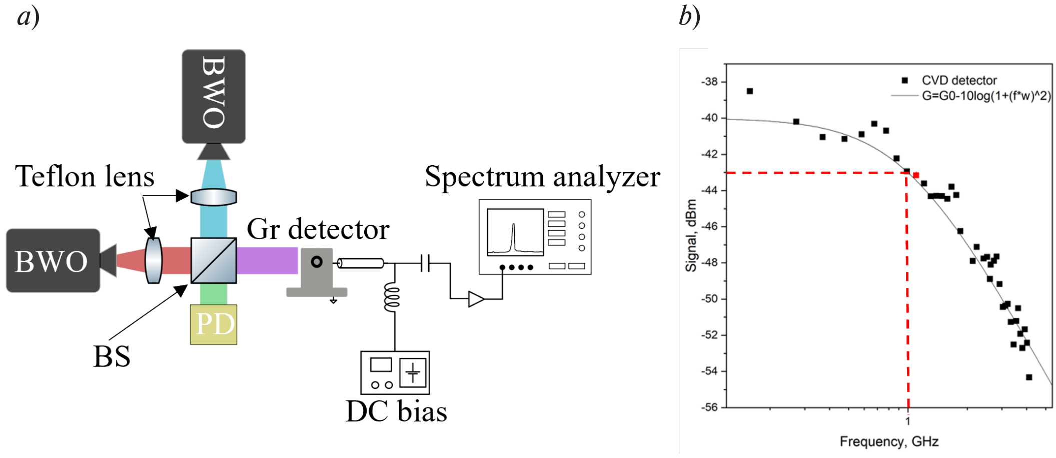

Fig. 2. Heterodyne detection scheme for a graphene detector integrated onto a silicon lens. Two backward-wave oscillator (BWO) operating at frequencies of 129–131 GHz were used for the measurements. The radiation was focused using teflon lenses and directed onto the graphene detector through a beam splitter (BS). Electrical readout was performed via a bias tee, with the high-frequency signal amplified by a cascade of amplifiers and measured using a spectrum analyzer (*a*); signal power from the graphene detector as a function of intermediate frequency, with the red dashed line indicating the 3 dB roll-off (*b*)

To evaluate the potential for high-speed operation of the photodetectors, we fabricated devices based on the same quality CVD graphene integrated into a THz antenna [14]. Next, we used a standard heterodyne mixing technique to measure the detector's bandwidth (Fig. 2, *a*). The heterodyne mixing principle involves feeding two similar-frequency signals from a generator to the detector. This produces sum and difference frequency signals at the mixer output, with the sum frequency filtered to yield an intermediate frequency (IF) signal. Terahertz radiation were provided by two tunable backward-wave oscillators. Each oscillator was equipped with a waveguide adapter fitted with a Teflon lens to produce plane-parallel terahertz radiation. This radiation passed through a beam splitter to the detector. The result of the dependence of the power at IF on the frequency is shown in Fig. 2, *b*. The bandwidth of our detector is 1 GHz and was limited by the setup.

Conclusion

Device characterization revealed promising photoresponse with responsivity and potential for high-speed operation exceeding 1 GHz bandwidth. The total response time of the photodetector is determined by a combination of the device's intrinsic response time and the bandwidth of the signal acquisition line (parasitic capacitances and inductances). The response time of 1 GHz we measured corresponds to the bandwidth of 1 cm of the aluminum lead wires and is not determined by the quality of the graphene. Improving the read out line should result in increased speed. Graphene-based waveguide-integrated photodetectors represent a significant advancement in ultrafast optoelectronics. Their compatibility with existing photonic platforms, combined with exceptional speed and broadband performance, positions them as key components for future high-speed communication and quantum photonic systems.

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REFERENCES

1. **Thomson D., et al.,** Roadmap on silicon photonics. J. Opt. 18 (2016) 073003.
2. **Chrostowski L., et al.,** Silicon Photonics Design: From Devices to Systems, Cambridge University Press. (2015).
3. **Arafin S., et al.,** Advanced InP photonic integrated circuits for communication and sensing. IEEE J. Sel. Top. Quantum Electron. 24 (2018) 1–12 .
4. **Nagarajan R., et al.,** InP photonic integrated circuits. IEEE J. Sel. Top. Quantum Electron. 16 (2010) 1113–1125.+
5. **Romagnoli M., et al.,** Graphene-based integrated photonics for next-generation datacom and telecom. Nature Reviews Materials. 3 (10) (2018) 392–414.
6. **Gabor Nathaniel M., et al.,** Hot carrier–assisted intrinsic photoresponse in graphene, Science. 334 (6056) (2011) 648–652.
7. **Ding Y., et al.,** Ultra-compact integrated graphene plasmonic photodetector with bandwidth above 110 GHz, Nanophotonics. 9 (2) (2020) 317–325.
8. **An P.P., et al.,** High-speed optical-waveguide integrated single-walled carbon nanotube bolometer, Applied Physics Letters. 125 (20) (2024).
9. **Gayduchenko I.A., et al.,** Manifestation of plasmonic response in the detection of sub-terahertz radiation by graphene-based devices, Nanotechnology. 29 (24) (2018) 245204.
10. **Schall D., et al.,** 50 GBit/s Photodetectors Based on Wafer-Scale Graphene for Integrated Silicon Photonic Communication Systems, ACS Publications. Collection. (2015).
11. **Xu Xiaodong, et al.,** Photo-thermoelectric effect at a graphene interface junction, Nano letters. 10 (2) (2010) 562–566.
12. **Castilla Sebastiốn, et al.,** Fast and sensitive terahertz detection using an antenna-integrated graphene pn junction, Nano letters. 19 (5) (2019) 2765–2773.
13. **Massicotte Mathieu, et al.,** Hot carriers in graphene–fundamentals and applications, Nanoscale. 13 (18) (2021) 8376–8411.
14. **Gazaliev A.S., et al.,** Graphene two terminal detector as THz mixer, In Journal of Physics: Conference Series IOP Publishing. 2086 (1) (2021) 012054.
15. **Rogalski A.M., et al.,** Two-dimensional infrared and terahertz detectors: Outlook and status, Applied Physics Reviews. (2019).

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