Terahertz detector utilizing a SiO₂/Graphene/SiO₂ sandwich suspended at the feed of a planar antenna

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Abstract. We report on the fabrication of a terahertz detector utilizing a SiO₂/graphene/SiO₂ sandwich suspended at the planar antenna feed. This design of the detector aims to enhance its sensitivity via weakening of the heat sink between graphene’s phonons and those of the substrate. We achieve complete suspension of the sandwich only in case of a low fill-factor of the antenna feed area. Evaluated DC parameters of the samples are consistent with those reported in the literature. The fabrication process developed is suitable for implementing the detector proposed for signal frequencies up to several terahertz.

1. Introduction
Terahertz frequency range is gradually mastered, and terahertz receivers are currently in demand in numerous applications. Despite worse sensitivity compared to that of superconducting competitors, terahertz detectors utilizing graphene produced by the means of chemical vapor deposition (CVD) have certain advantages. Namely, a) they are naturally compliant with integrated circuits making use of various semiconductor platforms, b) recent advances in their development suggest the performance competitive with that of planar Schottky diodes (PSD) [1], c) this performance can be achieved at less technological expenses. For that to happen, however, certain technical issues have to be resolved.

![Figure 1. Layer diagram of the graphene based structure proposed.](image_url)
In this paper we report on the fabrication of a terahertz detector utilizing a SiO$_2$/graphene/SiO$_2$ sandwich suspended at the feed of a planar antenna (figure 1). Such a design of the detector is meant to enhance its sensitivity by enlarging the time constant through weakening of the heat sink between graphene’s phonons [2] and a phonon reservoir presented by bulk Si-GaAs under the sandwich.

2. Fabrication process

To produce the detector, we relied on a 450 μm thick Si-GaAs (100) wafer to make the fabrication process partially compliant with that of the PSD with a Г-shaped anode suspended bridge earlier developed by us [3]. Referring to figure 2, the modified technological route contains six key steps:

- fabrication of alignment marks with further deposition of a SiO$_2$ sublayer (I),
- fabrication of the outer part of terahertz antenna followed by transfer of a CVD graphene (II),
- glancing angle deposition of ohmic and rectifying contacts to graphene (III),
- fabrication of the inner part of terahertz antenna (IV),
- encapsulation of graphene with a SiO$_2$ cover and plasma etching of unprotected regions (V),
- wet etching of GaAs (VI).

To remove organic residuals, GaAs wafer surface was pretreated by O$_2$ plasma. For steps I-II relying on a lift-off photolithography, we chose AZ 1512 HS positive photoresist, which was spread by centrifugation on a GaAs wafer at 6000 rpm. HMDS was used as an auxiliary adhesive layer. Thermoresistive evaporation was employed to produce the alignment marks and the outer part of terahertz planar spiral antenna presented by Ti/Au (5/200 nm) bilayers. A 50 nm thick SiO$_2$ sublayer that eventually serves as a foundation for graphene microbridge was sputtered through opening in e-beam resist by e-beam evaporation technique ensuring precise control of the thickness. Lift-off e-beam lithography within steps I, III-V was carried out with the aid of PMMA/MMA simultaneously providing high resolution and thickness required. Footprint of the SiO$_2$ sublayer was similar to that of the antenna inner part with a spatially-spanned load at its feed.

As shown in the literature [4], electrical properties of graphene significantly change if it comes into contact with photoresist during processing. And removal of photoresist after lift-off process can cause additional damage to graphene monolayer film. Thus, we had to avoid using AZ 1512 HS after transferring CVD graphene to the wafer basic transfer process is described elsewhere [5]. Moreover, fabrication of the outer part of terahertz antenna commonly performed closer to the end of technological route. Inability to use positive photoresist at step IV forced us to organize the order of steps as it is. Raman spectroscopy tests revealed that 30 % of the wafer area was suitable for further processing, i.e. it contained undamaged graphene monolayer film after the transfer.

We chose V and Au as materials for the ohmic and rectifying contacts to graphene. Glancing angle deposition technique [6] was used to implement a micro scale relative shift of the V and Au layers within
a V/Au (10/50 nm) metallization system deposited on graphene's top surface. For the deposition, we employed two-element composition of e-beam resists MMA/PMMA providing negative angle of inclination after development. Due to relatively small spacing between the contacts (0.2 - 0.6 μm) it took certain effort to fabricate them. Thus, the parameters of lithography process accompanying the deposition were optimized to ensure implementation of the geometry required. The sufficient dose was found by fixing the development time and varying cathode current along with sleep-in-point time of e-beam. Details of the glancing angle deposition process conducted are shown in figure 3(a, b).

![Figure 3](image)

**Figure 3.** Diagram of glancing angle deposition process: (a) Fabrication of ohmic contact to graphene (V/graphene); (b) Fabrication of rectifying contact to graphene (Au/graphene).

Prior to the fabrication of the antenna inner part, we processed the wafer by O₂ plasma to etch the graphene within its footprint (through opening developed in e-beam resist) and, consequently, to exclude possible AC shunting of the antenna metallization during operation of the detector. Further fabrication of a 75 nm thick SiO₂ cover overlapping the antenna feed area was followed by the removal of unprotected graphene regions in O₂ plasma. Both the SiO₂ sublayer and SiO₂ cover acted as etch-stoppers during the implementation of a SiO₂/graphene/SiO₂ sandwich suspended at the antenna feed.

During step VI, the local removal of the Si-GaAs underneath the sandwich was maintained through a dual sided opening (on both sides of the line connecting the antenna feed points) in PMMA positive e-beam resist intended for the access of wet etchant based on ammonia solution.

The fabrication process described hereinabove was employed to produce a set of terahertz detectors utilizing the suspended SiO₂/graphene/SiO₂ sandwich.

### 3. Results and discussion

Figures 4(a,c) provide images from a scanning electron microscope (SEM) for the detectors with different areas of graphene microbridge, the labels are denoted in figure 4(b).

![Figure 4](image)

**Figure 4.** (a) SEM image of sample #1; (b) Layer diagram of the sample; (c) SEM image of sample #2.

As one can clearly see, sample #1 (with a 0.6×6 μm² area of the microbridge) does not utilize a fully suspended SiO₂/graphene/SiO₂ sandwich, whose central part contacts the SI-GaAs substrate noticeably.
The total contact area is $1.3\times4 \text{ \mu m}^2$, whereas the contact of SI-GaAs to the region underneath graphene microbridge has significantly smaller area of $1.3\times0.6 \text{ \mu m}^2$. We achieved the complete suspension of a SiO$_2$/graphene/SiO$_2$ sandwich only in case of a low fill-factor of the antenna feed area (sample #2), i.e. for graphene microbridge of $0.2\times2 \text{ \mu m}^2$. Indeed, this geometry enables bigger opening in the e-beam resist which enhances access of wet etchant to the SI-GaAs being removed. If we had tried to make bigger openings in the resist and/or to increase etching time we would have risked to excessively remove SI-GaAs underneath the antenna’s metallization and, consequently, to cause collapse or critical sagging of the microbridge. It is worth mentioning that the microbridge dimensions of $0.2\times2\text{ \mu m}^2$ and $0.6\times6\text{\mu m}^2$ were also chosen to avoid discontinuities along its length, since irregularities in graphene can be of a submicron scale [7].

To evaluate efficiency of the fabrication process developed, we characterized DC transport properties of the samples produced. Details on the samples' geometry and values of DC resistance measured are summarized in table 1.

| $S_y$ [$\mu m^2$] | $N_o$ | $S_c$ [$\mu m^2$] | $R_{meas}$ [$\Omega$] |
|-----------------|------|-----------------|------------------|
| 0.6×6           | 0.6 $\mu m$/6 $\mu m$ | 26.7             | \{370; 350\}     |
| 0.2×2           | 0.2 $\mu m$/2 $\mu m$ | 9.6              | \{900; 840\}     |

Here $S_y$ is the area of a graphene microbridge, $N_o$ is the number of squares in the microbridge, $S_c$ is the area of a V/graphene junction and $R_{meas}$ is the value of DC resistance of the sample measured. Graphene’s sheet resistance ($R_{sheet}$) and contact resistivity of a V/graphene junction ($\rho_c$) can be evaluated by equation (1). Making use of the two sets of data presented in the table, one can calculate $R_{sheet}$ and $\rho_c$ values.

\[
R_{meas} = N_o R_{sheet} + \rho_c / S_c
\]  

Evaluated DC parameters of the samples produced are consistent with those reported in the literature [8]: graphene’s sheet resistance of $728\pm38 \Omega$/square and the contact resistivity of a V/graphene junction of $77\pm9\mu\Omega\cdot\text{cm}^2$ were obtained. We observed no drastic impact of the finishing removal of the SI-GaAs under SiO$_2$/graphene/SiO$_2$ on the samples’ DC transport properties.

To observe response to terahertz radiation at zero bias condition, it is vital to create asymmetry in graphene-based detector. In this work, the asymmetry is achieved via the implementation of an asymmetric contact doping, when graphene’s opposite sides are in contact with metals possessing different work functions [9]. For the samples produced, we measured the noise equivalent power (NEP) values of $9.4$ and $50.7 \text{ nW/Hz}^{0.5}$ at signal frequencies of 150 and 450 GHz, respectively. No bias voltage or current were applied to the samples during the measurements. Experimental setup was based on a solid state source utilizing microwave frequency synthesizer followed by a series of frequency multipliers and was similar to that previously employed by us in [10]. When mismatch with antenna is corrected for (the detector impedance is estimated based on $R_{meas}$ and RC-model of a graphene/metal junction [11]), the NEP values can be reduced to 1 nW/Hz$^{0.5}$ at 150 GHz and 6 nW/Hz$^{0.5}$ at 450 GHz.

4. Conclusion

We report on the fabrication of a terahertz detector utilizing a SiO$_2$/graphene/SiO$_2$ sandwich suspended at the planar antenna feed. Complete suspension of the sandwich was achieved only in case of a low fill-factor of the antenna feed area. It is known that the deviation of the spiral antenna inner part from a self-complementary structure leads to the decrease of antenna efficiency at the upper edge of its input frequency range [12]. The minimum dimension, at which this deviation can still be tolerated, is ultimately limited by the resolution requirements imposed on the fabrication of graphene microbridge (equipped with an ohmic contact) with 50-100 $\Omega$ impedance. Therefore, we suggest that the proposed
design within the fabrication process developed is suitable for the implementation of a graphene-based detector effective at signal frequencies up to several terahertz. Results of our study of DC and AC parameters of samples produced within the fabrication process developed are compliant with this suggestion.

Acknowledgments
We acknowledge support of the Russian Science Foundation grant No. 19-72-10156.

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