Plasmonic terahertz detectors for biodetection

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A report is presented on the biodetection capabilities of plasmonic terahertz detectors. Large changes in the terahertz response of plasmonic detectors loaded with solutions of globulin-free bovine serum albumin, arginine and heparin were measured for concentrations that did affect the device transfer characteristics. The consistent change of the response characteristics with specimen type and concentration can be used to identify and quantify biological and chemical substances. The device structure makes it suitable for use as a building block of a biosensor with integrated processing capabilities.

Introduction: Detection of biological and chemical agents is important in many fields including defence, medicine, genomics, and the pharmaceutical and food industries. Utilisation of terahertz radiation for this purpose is promising since molecules of many chemical compounds have rotational and vibrational modes lying in the same energy range as terahertz radiation. Specific terahertz absorption patterns allow the detection, identification and quantification of such molecules. Terahertz time domain spectroscopy (TDS) [1], terahertz dielectric spectroscopy [2], surface functionalised resonators [3] and photonic crystal waveguides [4] have been proposed to detect and identify chemical and biological substances.

Recently, semiconductor plasmonic detectors have attracted a great deal of attention for resonant and nonresonant terahertz detection and terahertz imaging. These unique devices have the inherent advantage of tunability by electrical bias which would eliminate the complex and bulky filters, gratings, moving mirrors, or other elements to analyse the spectrum of incoming radiation and might enable simple spectroscopy systems with a broadband source and the plasmonic tunable detector. Detection of terahertz radiation by plasma waves has been demonstrated using commercial AlGaAs/GaAs FETs [5], double quantum well FETs [6], AlGaN/GaN HFETs [7]. Si MOSFETs [8] and more recently by AlGaN/GaN HFETs with periodic grating-gates [9].

As shown in [10], the device response is very sensitive to the boundary conditions at the gate edges with electric field changes within a few nanometres causing dramatic changes in the plasmonic device’s terahertz response. Therefore, placing organic molecules in the proximity of the gate edges induces large changes in the terahertz response even if the device current voltage characteristics remain unchanged. In this Letter, we report on using this effect for exploring the biological and chemical detection capabilities of the plasmonic terahertz detectors.

Results and discussion: Commercial AlGaAs/GaAs HEMTs from Fujitsu were used in the experiments as plasmonic terahertz detectors. The gate width, \( W \), was 200 \( \mu \)m, and the nominal gate length \( L_g \) was 250 nm. Fig. 1 shows the transfer characteristics at \( V_D = 50, 100 \) and 150 mV corresponding to the linear part of output current-voltage characteristics of the device. The threshold voltage was \( V_{th} = 0.55 \) V. To assess the performance of the detectors we investigated the bovine serum albumin (BSA) and L-arginine (which have been investigated previously [1,11]) and heparin. The essentially-globulin-free BSA and L-arginine powders were purchased from Sigma-Aldrich. They were dissolved in water with varying rates resulting in homogenous solutions with concentrations of 0.01–0.1 mg/ml. Heparin was prepared in the same way with the concentrations of 1–10 mg/ml. 10 ml drops of the solutions were transferred on to the plasmonic terahertz detectors by adjustable volume pipettes. The terahertz responses of the devices were measured after the water evaporated.

The photoresponse measurements were performed using a 600 GHz Gunn diode as a radiation source. The maximum output power of the Gunn diode was 300 \( \mu \)W. A waveguide finished with a cone was connected to the output of the Gunn diode to outcouple the radiation. The radiation beam was not focused and the radiation beam diameter at the sample holder was much larger than the device size. No special coupling antennas were used and the radiation was coupled to the device through metallisation pads and bonding wires. The radiation intensity was modulated with a mechanical chopper at 140 Hz and the open-circuit source-drain voltage was measured by a lock-in amplifier with the input impedance of 10 M\( \Omega \) while the source was grounded and the gate voltage was changed by a Keithley source-meter.

The detector transfer characteristics before and after covering with biological specimens are shown in Fig. 1. It is important to point out that deposition of biological specimens did not cause any change in their electrical properties. Fig. 2 shows the gate bias dependence of the terahertz response after a drop of heparin solution with a certain concentration was placed on the detector and the whole water evaporated. As can be seen, the response decreases consistently with increasing concentration of the heparin solution. For comparison purposes, we can define the relative chemical sensitivity of our detectors as

\[
\delta = \frac{\Delta R_L/R_L}{\Delta \lambda}
\]

where \( \Delta R_L \) is the change in the terahertz response of the loaded detector corresponding to the change in the concentration \( \Delta \lambda \) of the specimen under consideration and \( R_L \) is the response of the unloaded device without a specimen at the same gate bias with \( \Delta R_L \). We can estimate that the average relative chemical sensitivity of our device for the heparin \( \delta \approx 0.05 \text{ml/mg} \).

The response of our detector to incoming terahertz radiation when it is covered with arginine solutions changes in a similar fashion to the case for heparin solutions as shown in Fig. 3. The response decreases with increasing concentration of the Arginine solution and reaches down to zero above 0.1 ml/mg. The relative chemical sensitivity of plasmonic terahertz detectors for arginine can be estimated as \( \delta \approx 6 \text{ml/mg} \).

Finally, Fig. 4 shows the gate bias dependencies of the detector’s terahertz response when it was loaded with BSA solutions with different concentrations. Although the shape is different since the overall detector response shape was different than the other two detectors even without any biological specimen placed on it, the response amplitude decreases with increasing concentration of the BSA, just like the other cases. The relative chemical sensitivity of the detector for BSA can be estimated as \( \delta \approx 2.3 \text{ml/mg} \) by using (1).
Conclusion: We have demonstrated that the shape and amplitude of the response of plasmonic semiconductor terahertz detectors changes when they are covered with solutions of biological substances. The amplitude decreases with increasing concentration of the solution, which could be used for accurate measurement of concentration. The results clearly show that plasmonic terahertz detectors can be effectively used as biosensors to detect and quantify the concentrations or biological molecules. The device structure makes it suitable for use as a building block of a biochip with integrated processing capabilities.

Development of this technique could benefit genomics and proteomics research, the pharmaceutical and food industries and homeland security.

© The Institution of Engineering and Technology 2008
8 October 2008
Electronics Letters online no: 20082886
doi: 10.1049/el:20082886
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References

Fig. 3 Terahertz response of plasmonic detector after covering with arginine solutions with different concentrations
(i) before biological specimen
(ii) 0.01 mg/ml
(iii) 0.05 mg/ml
(iv) 0.1 mg/ml

Fig. 4 Terahertz response of plasmonic detector after covering with BSA solutions with different concentrations
(i) before biological specimen
(ii) 0.01 mg/ml
(iii) 0.05 mg/ml
(iv) 0.1 mg/ml

ELECTRONICS LETTERS 20th November 2008 Vol. 44 No. 24