The potential for sensitivity enhancement by the thermoelectric effect in carbon-nanotube and graphene Tera-FETs

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Abstract. We report on terahertz (THz) measurements with graphene field-effect transistors with integrated antennas (Tera-FETs) and lay special emphasis on thermoelectric contributions to the detected THz photoresponse. Graphene Tera-FETs with integrated broad-band bow-tie antennas were fabricated in a CVD-based growth process and were successfully applied for detection at 600 GHz with optical NEPs down to 515 pW/$\sqrt{}$Hz. While rectification of THz radiation by (distributed) resistive mixing of charge-density waves induced in the gated transistor channel region is well known, significant additional contributions to the detected signal have experimentally been observed and hot-carrier thermoelectric effects have been identified as a possible origin of these signals. We also observe similar signal contributions in carbon-nanotube transistors.

1. Introduction

Detectors for terahertz (THz) radiation employing field-effect transistors (Tera-FETs) have been implemented in various material systems for more than one decade (for an overview see, e.g., [1]). The detection principle is based on the self-mixing properties of charge-density (plasma) waves induced in the transistor channel by an applied THz signal [2]. The rectification mechanism is not limited by conventional cut-off frequencies of the transistors and has successfully been demonstrated up to several THz at room temperature (e.g., [3]). Besides optimization of the transistor geometry, integration of antenna structures for radiation coupling is a crucial step to realize high-sensitive THz detectors. In combination with novel material systems, e.g., carbon-based materials such as graphene and carbon-nanotubes (CNTs), Tera-FETs can also serve as powerful tools for the investigation of physical properties, such as transport properties and carrier dynamics of the materials.

In this contribution, we report on the detection of THz radiation with Tera-FETs using graphene or CNTs as the transistor channel. We fabricated sensitive CVD-grown graphene Tera-FETs with integrated bow-tie antennas [4] and characterized them at 600 GHz, where in addition

to the self-mixing signal by plasma wave rectification, we also observe signal contributions which we attribute to a hot carrier photothermoelectric effect arising due to the specific device geometry. We observe similar contributions in other material systems, particularly pronounced in CNT Tera-FETs, which offers the potential for significant sensitivity enhancement of carbon-based Tera-FET detectors.

2. Self-mixing of plasma waves in Tera-FETs

The detection principle of Tera-FETs is based on nonlinear self-mixing of radiation-induced charge density oscillations (plasma waves) in the gated transistor channel region [2]. In most cases, in particular at room temperature, strong damping leads to a decay of the charge density waves before they can reach the end of the channel - they are overdamped ($\omega\tau \ll 1$). Nonetheless, efficient rectification due to (distributed) resistive self-mixing is present in this case and has been shown to yield high-sensitive THz detectors, which can compete with or even exceed the performance of other established detector technologies in this frequency regime, e.g., Schottky-diode-based, pyroelectric, or acousto-optic detectors. The work presented in this contribution is focusing on the case of non-resonant mixing. In Tera-FETs using CNTs as the active transistor channel, however, the transport of charge carriers through the channel can be ballistic and resonances at the p-n-p-junctions of the gated channel region have been observed [5].

Efficient detection by self-mixing of plasma waves in a FET is only possible when certain boundary conditions for the transistor are fulfilled. Most important, the coupling of the incoming high frequency radiation to the transistor contacts must be asymmetric with respect to the source and drain terminal [2]. Otherwise, plasma waves would be launched into the channel from both sides and the signals generated by self-mixing of the waves would cancel out. Asymmetric coupling can be introduced by various means, e.g., by creating an asymmetric transistor geometry or by using a double-transistor layout with parallel signal read-out at the virtual AC ground in the symmetry plane [3]. Another often employed realization of full asymmetric coupling is the introduction of a shunting capacitance between, for example, the gate and drain terminals. In this way, the applied THz signal will be concentrated with full field strength at the source terminal, while the drain terminal forms an AC ground. Under the above considerations, the self-mixing voltage response ΔU measured between drain and source can roughly be predicted from measurements of the DC conductance σ versus gate voltage U_g and the applied THz amplitude U_a reaching the transistor by [6]

$$\Delta U \propto \frac{U_a^2}{4}\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}U_g}. \tag{1}$$

3. Thermoelectrics

In measurements of the photoresponse of Tera-FET detectors, additional contributions to the detected voltage (current) signal can be observed in various material systems. It has been suggested before [7], that the observed signal contributions can be of thermoelectric origin stemming from the specific device geometry. The required asymmetric coupling conditions for the incident radiation discussed above lead to a strong localization of the electric field at one side of the transistor channel. This can result in a local heating of charge carriers. For capacitive gate-drain coupling, for example, only the source side of the channel is heated while the drain side (AC ground) remains at the temperature of thermal equilibrium.

A local difference in the electronic temperature in a material gives rise to a voltage, which is known as the thermoelectric or Seebeck effect. We attribute the additional signals in our measurement to this effect. We observe especially pronounced contributions in graphene and CNT transistors. It has been shown in a number of studies that in graphene, after initial relaxation of excited carriers, electron-lattice interactions can be strongly suppressed due to high
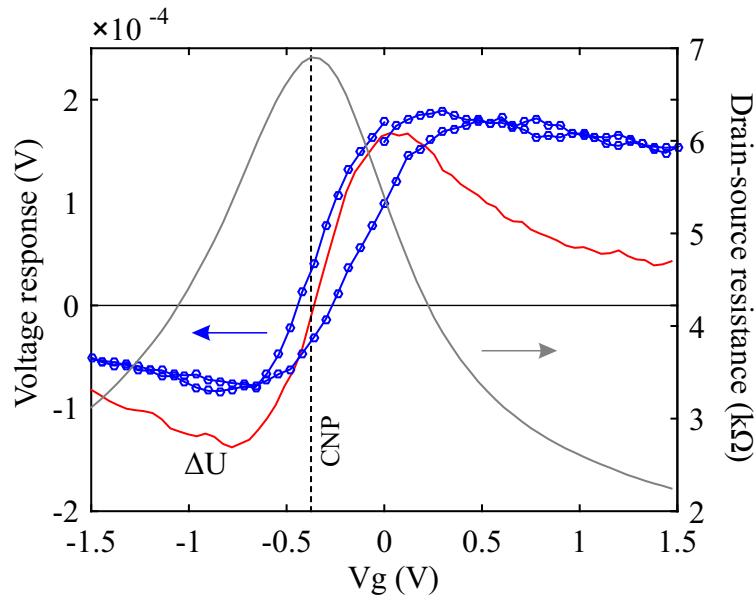
Figure 1. Photoresponse of a CVD-grown graphene Tera-FET at 600 GHz (blue line/symbols, left axis). The gray line (right axis) is the DC resistance of the device. The red line shows the anticipated THz response ΔU due to resistive self-mixing for an arbitrary $U_a \sim 25\text{mV}$.

optical phonon energies and long acoustic phonon scattering times, leading to a distribution of hot carriers even under weak electrical driving [8, 9]. In addition, due to the different nature of charge carriers in graphene (electrons or holes) depending on the applied gate voltage, the resulting thermoelectric effect can be of positive or negative sign, thus, enhancing or decreasing the detector's self-mixing response signal.

Figure 1 shows measurements of the photoresponse of a graphene Tera-FET performed at 600 GHz on the left axis (device geometry and measurement setup similar to the one in [4]). The transistor was made of single-layer graphene grown in a CVD process and transferred to a Si/SiO$_2$ substrate. On the right axis of the figure, the light gray line shows the drain-source resistance measured at DC. From the resistance, the predicted self-mixing response ΔU of the Tera-FET can be calculated using Eq. (1). The result (for an arbitrary applied amplitude U_a for reasons of visualization) is plotted in the figure as a solid red line. Comparing the anticipated and the measured voltage response of the detector, the contributions of the thermoelectric signal can clearly be seen. In particular, at the charge-neutral-point (CNP) of the graphene, no self-mixing signal should be present, since the derivative of the channel conductivity vanishes at this point. The Tera-FET, however, shows a large signal at this gate bias and in a previous study[4] it has been shown that even a low difference in the electronic temperature of ~ 1 K can account for such a thermoelectric contribution to the photoresponse. It can also be observed that as expected, depending on the type of charge carriers, on the right side of the CNP, the contribution to the absolute self-mixing signal is additive while on the left side it is negative. We also characterized the sensitivity of our detectors and determined an optical noise-equivalent power (NEP) of 515pW/$\sqrt{\text{Hz}}$ [4], which is almost comparable to other advanced THz detector technologies, showing that CVD-grown graphene can be used to fabricate sensitive Tera-FET detectors for the THz frequency range.

In measurements performed with transistors realized in various other material system, namely silicon CMOS, GaN and CNTs (data not shown here), we observe similar signal contributions to the self-mixing response. For CMOS detectors, the effect is only visible at cryogenic

temperatures, but even for GaN it is observable at room temperature. Here, the thermoelectric contribution is of opposite sign compared to the self-mixing signal. A phase change in the photoresponse is observed. Moreover, we observe a strongly pronounced effect in the investigated CNT transistors at room temperature. Remarkably, no phase change is present in this case meaning that the thermoelectric signal adds positively to the self-mixing. We qualitatively explain this behaviour by using Motts formula for the calculation of the Seebeck coefficient:

$$S = -\int_{E_C}^{\infty} g(E)f(E,E_F)(1-f(E,E_F))\frac{E-E_F}{k_B T}dE \qquad (2)$$

where $f(E,E_F)$ is the Fermi function, E_F the Fermi energy, k_B Boltzmann's constant, T is temperature and $g(E)$ is the density of states. The latter is constant for two-dimensional materials but is proportional to $1/\sqrt{E}$ for one-dimensional systems. In this case, Evaluation of Eq. (2) yields a sign reversal in the Seebeck coefficient. Therefore, the resulting thermoelectric current or voltage also shows a reversed sign. Hence, the contribution to the total measured photoresponse is of the same phase as the self-mixing signal, thus, increasing the measured photoresponse. The observation of this theoretical prediction in our measurements is another strong indication that the additional signal contributions are indeed of thermoelectric origin. Although the effect shows up as a side effect in our graphene and CNT detectors, with proper device design THz detectors could be optimized to realize a sensitivity enhancement of the self-mixing effect by the hot carrier thermoelectric effect.

4. Conclusion

We fabricated Tera-FET detectors in a set of materials, in particular graphene and CNTs. Besides efficient detection by plasma wave self-mixing, contributions to the detected signal, which cannot be explained by the plasmonic mixing picture, have been observed in all investigated material systems. We attribute these signals to a photo-thermoelectric effect, arising from the required asymmetric radiation coupling. We discuss the influence of these contributions on the self-mixing effect and show that the strength of the thermoelectric effect is especially pronounced in graphene and CNTs and there can add positively to the plasmonic self-mixing. Hence, these materials offer the potential to strongly enhance or exceed the self-mixing response and could be optimized for the realization of a new set of THz detectors, exploiting the thermoelectric effect. So far, no detailed quantitative analysis of the thermoelectric effect in Tera-FETs is available and is subject to further in-depth investigation.

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