Proceedings Paper:

Hunter, N, Mayorov, AS, Wood, CD et al. (6 more authors) (2015) Spatially Resolved On-Chip Picosecond Pulse Detection Using Graphene. In: IEEE 2015 40th International Conference on Infrared, Milimeter, and Terahertz Waves (IRMMW-THz). 40th International Conference on Infrared, Millimeter, and Terahertz Waves, 23-28 Aug 2015, Hong Kong. IEEE . ISBN 9781479982721

https://doi.org/10.1109/IRMMW-THz.2015.7327831

Spatially Resolved On-Chip Picosecond Pulse Detection Using Graphene

N. Hunter, A. S. Mayorov, C. D. Wood, C. Russell, M. C. Rosamond, L. H. Li, E. H. Linfield, A. G. Davies, and J. E. Cunningham
School of Electronic and Electrical Engineering, University of Leeds, Woodhouse Lane, Leeds, LS2 9JT, UK

Abstract—We present an on-chip time domain terahertz (TD-THz) system in which picosecond pulses are generated in low-temperature-grown gallium arsenide (LT-GaAs) and detected in graphene. The detected pulses were found to vary in amplitude, full width at half maximum (FWHM), and DC offset when sampled optically at different locations along a 50-µm-long graphene photoconductive (PC) detector. The results demonstrate the importance of detection location and switch design in graphene-based on-chip PC detectors.

I. INTRODUCTION

COHERENT pulse detection in an on-chip TD-THz system is often achieved using photoconductive materials, such as LT-GaAs. Graphene is a promising material for PC detection of THz radiation as it possesses high room temperature carrier mobility, short hot-carrier lifetime and absorbs 2.3% of free-space infrared light, despite being only one atom thick. We have recently demonstrated the operation of graphene PC THz detectors operating up to 600 GHz when integrated into an on-chip, planar waveguide [1]. These graphene PC devices were also used to demonstrate THz pulse generation; therefore, graphene may be an important material in the development of on-chip THz systems that use 1.55 um laser technology. A full understanding of graphene PC switch properties is therefore necessary to further develop graphene THz devices, with potential applications in spectroscopy, security and communications.

In this paper, we demonstrate the generation of THz pulses in LT-GaAs which are coupled to a single wire THz waveguide and detected by graphene at room temperature. A pulse is first both generated and detected using LT-GaAs in order to characterize the emission switch performance and to measure the pulse velocity along the waveguide. This reference measurement is then compared to a pulse detected in graphene and the key differences are discussed. Finally, we investigate changes in the detected pulse characteristics as a function of optical probe location on the graphene switch. These measurements provide a better understanding of graphene PC detectors and show how the THz signal can be optimized through careful positioning of the detection location.

II. RESULTS

An on-chip system, shown in Fig 1, consisted of a quartz substrate, a pair of LT-GaAs PC switches, a 9-µm-wide gold planar Goubau line (PGL) waveguide and a 50-µm-long, 9-µm-wide graphene PC detector. The graphene PC detector was located at a gap in the PGL 500 µm away from the LT-GaAs switches. The CVD grown graphene was transferred above the PGL with an overlap of 5 µm at either side of the gap for contact (as shown in the lower inset of Fig 1). Shipley S1813 photoresist was used to support the graphene and to

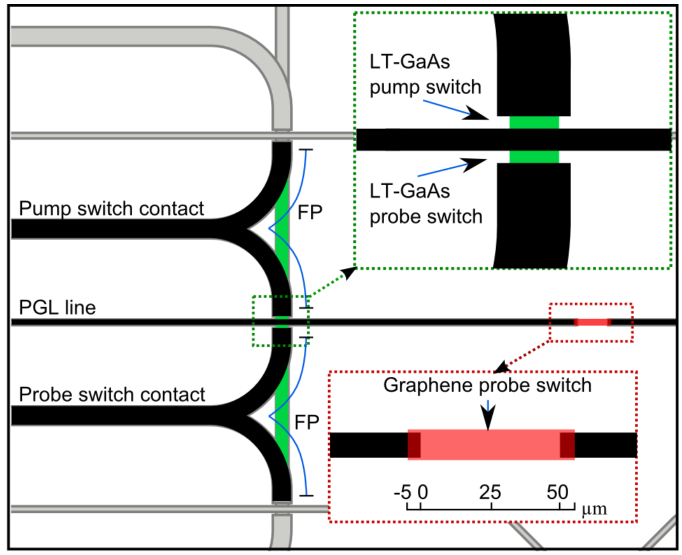

Fig 1: Device schematic, where the black and grey regions are Au (grey regions are unused in these measurements), green is LT-GaAs, and red is the graphene switch region. The blue lines labelled FP are the paths of the Fabry-Pérot reflections. For reference measurements the LT-GaAs pump and probe switches are illuminated by the pump and probe beams. In the graphene detection measurements, the LT-GaAs pump switch was used to generate the pulse and the probe beam was scanned along the length of the graphene probe switch.

provide a (p-type) doping in the range of $6 \pm 2 \times 10^{12}$ cm^{-2}, as determined by Raman spectroscopy. The device was mounted in a TD-THz system, in which a Ti:Sapphire laser emitting 780 nm, 100 fs pulses at a rate of 80 MHz was split into separate pump and probe beams. The pump beam was used to illuminate the LT-GaAs switch with 10 mW average power and switch bias of 30 V. The probe beam was focused using an objective lens to a spot size (FWHM) of 5.5 µm. The probe beam was chopped to allow lock-in detection of the THz signal, and an optical delay stage was used to alter the relative arrival time between the two beams.

Initially the probe beam was used to illuminate the LT-GaAs switch adjacent to the generation switch. The THz signal was measured by recording the current across the probe switch as a function of optical delay between the two beams. This provided a reference measurement of the signal produced in the LT-GaAs (Fig 2a), where the main peak had a FWHM of 2 ps, and was followed by a reflection from the graphene/metal interface after a propagation time of 6 ps. The reflection was used to determine a velocity for the pulse on the PGL transmission line of 1.7×10^{8} m s^{-1}. Small signal oscillations were observed following the large reflection, which arise from Fabry-Pérot (FP) reflections in the probe arms from the feature labelled FP in Fig 1. The period of these reflections was 4 ± 0.3 ps, corresponding to pulses propagating at the calculated velocity, over the distance of the FP cavity.

The probe beam was then moved to illuminate the graphene

PC switch for pulse detection. Time-domain scans recorded the current flow through the graphene channel as a function of both the probe beam delay time, and the absolute position of the optical probe on the graphene PC switch. The largest amplitude pulse was measured 5 µm after the first graphene/metal contact (Fig 2b), and arrived 3 ps after the excitation of LT-GaAs generated pulse. This pulse had a FWHM of 2.2 ps, showing performance very similar to the reference pulse. Unlike the reference pulse however, a large reflection was not seen from features in the transmission line, as the metal LT-GaAs switch design produces negligible reflections in comparison to the very high impedance graphene switch [2]. Oscillations were seen after the main pulse, where the period was in the same range as the reference pulse and hence are attributed to the same FP cavity region as mentioned previously.

Pulses generated in the LT-GaAs, were detected at 24 consecutive locations in a line along the graphene switch, spaced 2.6 µm apart. The resulting time domain pulses (Fig 3a) were each fitted with a Lorentzian function to allow the amplitude, FWHM, and DC offset parameters for each position to be determined. A DC current, which is thought to be caused by the photo-thermoelectric (PTE) effect [3], was observed near the graphene/metal contacts. Specifically, the graphene contact closest to the LT-GaAs displayed negative photocurrent and the furthest a positive photocurrent.

The measured AC current is dependent on the THz electric field that is across the area of illumination, E_{THz}, and the change in conductivity of the graphene, $\delta\sigma$:

$$I(t) \propto \int_{-\infty}^{+\infty} E_{THz}(\tau)\delta\sigma(t-\tau)\, d\tau \,. \qquad (1)$$

The maximum pulse amplitude, 5 µm after the first graphene/metal interface, is where all absorbed optical energy contributed to a conductance change, as opposed to being absorbed by the graphene/metal contact. Across the graphene channel, the THz field was expected to remain constant owing to an even distribution of the field between the metal contacts.

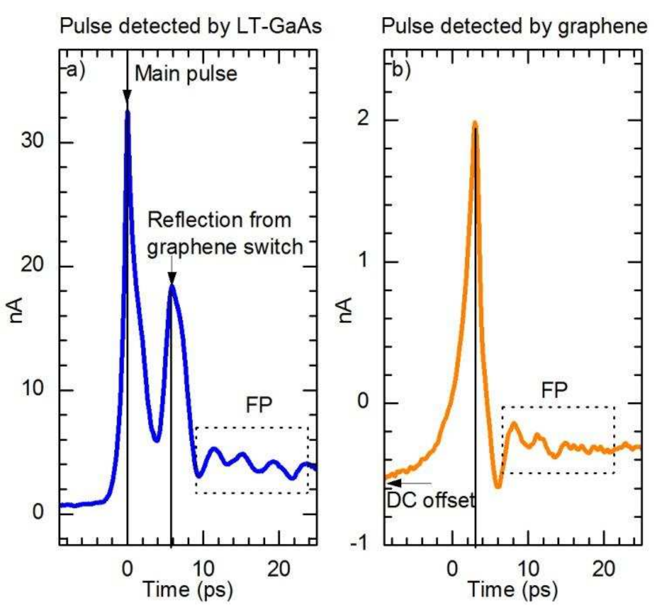

Fig 2: Pulses detected on the on-chip TD-THz system, where a) is the reference pulse measured at LT-GaAs adjacent to the generation switch, and b) is the pulse detected by graphene 500 µm along the THz waveguide.

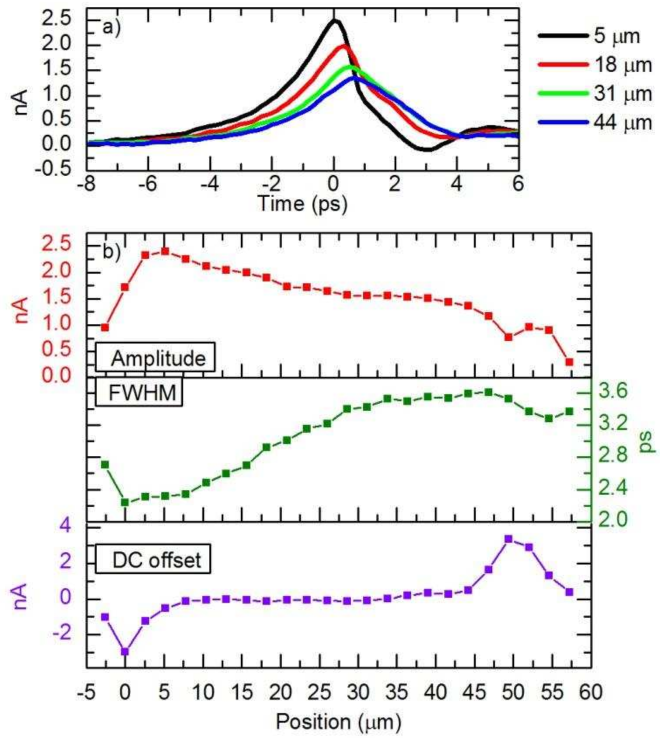

Fig 3: Pulses detected in graphene as a function of position where 0 µm is the nearest graphene/metal interface and 50 µm is the furthest from the LT-GaAs switch. a) Time domain pulses at four locations with the DC component removed to show the amplitude relationship. b) Fitted Lorentzian peak parameters for amplitude, FWHM and DC offset across the full graphene

However, the amplitude of the pulse decayed across the length of the sheet. Group velocity dispersion, caused by the capacitance in the gap, is thought to be the primary cause of this as the total integrated area of each pulse between 5 µm and 40 µm remained constant, whilst the FWHM increased from 2.3 ps to 3.5 ps.

III. SUMMARY

The detection of few-picosecond-duration pulses using a 50-µm-long graphene PC detector was studied. The detected signals vary in amplitude, pulse-width and DC offset depending on precise spatial position of the detection pulse on the graphene switch. The photo-thermoelectric effect at the graphene contacts was responsible for the changes in DC offset, whereas dispersive effects in the graphene caused a spatial variation of the AC signal. This work demonstrates that the fast carrier dynamics of graphene are capable of detecting coherent THz radiation, and that optimization of the optical sampling beam is important to retain as much spectral information as possible.

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