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On-Chip Terahertz Modulation and Emission With Integrated Graphene Junctions

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ABSTRACT

The efficient modulation and control of ultrafast signals on-chip is of central importance in terahertz (THz) communications and a promising route toward sub-diffraction limit THz spectroscopy. Two-dimensional (2D) materials may provide a platform for these endeavors. We explore this potential, integrating high-quality graphene p-n junctions within two types of planar transmission line circuits to modulate and emit picosecond pulses. In a coplanar strip line geometry, we demonstrate the electrical modulation of THz signal transmission by 95%. In a Goubau waveguide geometry, we achieve complete gate-tunable control over THz emission from a photoexcited graphene junction. These studies inform the development of on-chip signal manipulation and highlight prospects for 2D materials in THz applications.

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Emerging chip-scale technologies operating in the terahertz (THz) band^{1–4} promise compact devices for sensing,⁵ imaging,⁶ security,⁷ and communications.^{8–10} A vital requirement for these pursuits is the design of interconnects, sources, and modulators to control and guide high frequency signals on chip. Two-dimensional (2D) materials are an appealing option owing to their ultrafast charge carrier dynamics and intrinsic compactness. Previous work has demonstrated sensitive THz detectors^{11–17} and transistors with cutoff frequencies reaching 50 (Ref. 18) and even 350 GHz.¹⁹ Modulation of free space THz radiation has also been demonstrated using graphene^{20–27} and molybdenum disulfide (MoS₂),^{28,29} achieving modulation depths of 100% and modulation speeds as high as 110 MHz.³⁰ Harnessing ultrafast signals on-chip may additionally enable new spectroscopic measurements for fundamental science. Confinement of THz radiation in planar transmission lines enhances spatial resolution, allowing spectroscopy of materials well beyond the diffraction limit for free space THz measurements. Recent examples include probes of the optical conductivity of graphene in both thermal equilibrium,³¹ as well as under intense optical drive,³² and picosecond magnetization reversal in GdFeCo.³³

We investigate two on-chip spectrometer designs for THz modulation and emission using ultra clean graphene p-n junctions. In coplanar strip lines (CSs) and Goubau waveguides (GWs), we integrate graphene van der Waals heterostructures to directly modulate the line impedance using a local finger gate. Applying a gate voltage allows electrical control of on-chip THz transmission and emission. At low temperatures, we achieve 95% modulation depth in CS circuits, which are well explained by finite-difference time-domain simulations. Finally, introducing a pump beam to directly photoexcite the graphene junction in the GW geometry, we demonstrate gate-tunable emission from the graphene junction.

Our high frequency circuits contain a combination of photoconductive (PC) switches and graphene p-n junctions for the purpose of generation, modulation, and detection of on-chip THz transients (Fig. 1). Our devices are fabricated starting from silicon-on-sapphire (SOI) wafers, which are then dosed at 1×10^{15} ions/cm² with 100 keV oxygen ions. A subtractive process removes the silicon everywhere except where PC switches are desired, and waveguide circuits are subsequently patterned by standard photolithography and evaporation of titanium (10 nm) and gold (100 nm). The CS circuit [Figs. 1(a)–1(c)]

FIG. 1. Two on-chip THz circuits with integrated graphene p-n junctions. (a) Circuit diagram of the coplanar strip line (CS) geometry. The blue (dashed) and red (solid) boxes indicate the positions of the optical images in panels (b) and (c), respectively. The photoconductive (PC) switches are labeled with black arrows. (b) Optical image showing the locations of the PC switches used for both generation and detection of on-chip THz transients. The red box shows the location of the optical image in (c). (c) Cross-sectional model representation (above) and optical image (below) of the integrated graphene p-n junction. (d) Circuit diagram of the Goubau waveguide (GW) geometry. The blue (dashed) and red (solid) boxes correspond to the position of the optical images in panels (e) and (f), respectively. (e) Optical image of the PC switches in the GW circuit. (f) Cross-sectional model representation (above) and optical image (below) of the integrated graphene p-n junction.

consists of two 5 μm wide electrodes separated by 10 μm , resulting in a characteristic impedance of 121 Ω .³⁴ The GW circuit [Figs. 1(d)–1(f)] consists of a single 30 μm wide conductor, resulting in a characteristic impedance of $\approx 120 \Omega$.³⁵ In both circuits, we employ two PC switches [Figs. 1(b) and 1(e)] with a carrier relaxation time of 560 fs determined by time-resolved THz spectroscopy (Fig. S1). The right switch is photoexcited with a pulse from an amplified femtosecond laser with a 200 kHz repetition rate, an 800 nm wavelength, and a 25 fs pulse duration, which generates a THz transient. The left switch is then used to sample the time-domain profile of the propagating THz electric field transients using time-delayed pulses from the same laser. Figure S2 in the [supplementary material](#) shows a schematic of the setup and a detailed description of this measurement.

In both designs, we incorporate a graphene p-n junction, which directly modulates the line impedance. In the CS circuit, the ground line between the two PC switches is interrupted by a graphene junction composed of a monolayer graphene flake sandwiched between two boron nitride (hBN) flakes with a graphite flake employed as a finger gate [Fig. 1(c)]. In the GW circuit, the graphene junction forms a portion of the center conductor [Fig. 1(f)]. The carrier density is modulated at the center of graphene with a platinum finger gate. In both devices, the gate is electrically isolated to reduce the coupling of the transient pulses through the gate electrodes. The van der Waals heterostructures are stacked using the dry polymer method and edge contacted with chromium/palladium/gold (3 nm/15 nm/100 nm).³⁶ This junction geometry does not allow for complete control over the p-n junction response as there are ungated regions on both sides of the finger gates, as shown in the cross-sectional models in Figs. 1(c) and 1(f). Ideally, the ungated regions are undoped. However, we observe an asymmetry in the gate dependent transport—especially pronounced at low temperatures—that points to residual n-type doping [Figs. 2(g) and 3(a)]. This may arise from traps at the hBN-sapphire interface and photodoping by the generation and detection laser pulses³⁷ (Fig. S3).

At room temperature, we achieve the modest modulation of THz electric field transients in both geometries. Figure 2(a) shows the transmission time domain scans for the CS circuit at two different gate voltages. The readout current from the left PC switch is plotted as a function of time delay between the generation and detection laser pulses. Time zero has been arbitrarily chosen to coincide with the transient arrival at the readout switch. The transmitted transient is positive, and the Fourier transform reveals frequency components up to roughly 400 GHz [inset of Fig. 2(a)]. By varying the backgate voltage, the transient amplitude is modulated. Figure 2(b) shows the peak amplitude as a function of gate voltage where a total signal modulation of 24% is achieved. A color scale plot of the readout current as a function of gate voltage and time delay is shown in Fig. 2(d). The modulation follows the DC characteristics (see the [supplementary material](#) for mobility and residual doping estimates) of the device, shown in Fig. 2(c), with the CS transient amplitude increasing with increased channel resistance. The modulation of the picosecond transient is also directly correlated with the gate dependent transport, showing the same asymmetry between npn and nnn doping configurations. From the reflection coefficient for a series connected impedance ($\Gamma = Z/(Z + 2Z_0)$), where Z is the characteristic impedance of the transmission line and Z_0 is the graphene impedance,³⁸ we would expect a decrease in the transmitted transient amplitude with increased Z_0 , making the experimental results somewhat counterintuitive.

To better understand the time-domain response of our CS circuit, we carried out finite-difference time-domain simulations,³⁹ shown in Fig. S4. We find that when the simulated chemical potential is small and the graphene has the highest resistance, most of the transient is reflected because the ground line is effectively disconnected. Furthermore, at small chemical potentials, the amplitude of transmission inverts (changing sign) and a negative input pulse becomes a positive transmitted pulse. This can be seen in Fig. S4(b) at the lowest plotted chemical potential of $\mu = 0.01 \text{ eV}$. The amplitude of this peak is maximized at low chemical potential (high graphene resistance), matching the observations in Figs. 2(b) and 2(c). This regime allows for nearly complete modulation of the transmission in the CS circuit at lower temperatures where the p-n junction response is more dramatic.

FIG. 2. THz modulation in the CS circuit at room temperature [panels (a)–(d)] and 77 K [panels (e)–(h)]. (a) Readout current (I) plotted as a function of transient time delay (time) for two gate voltages (V_g). The inset shows the Fourier transform of the time domain scans in the main panel. (b) Peak current (I) plotted as a function of gate voltage (V_g). (c) DC resistance (R) as a function of V_g . The npn and nnn labels signify the p–n junctions created by residual doping and photodoping. (d) Colorplot of I as a function of V_g and time for all gate voltages explored. (e) I vs time at 77 K. The inset shows the Fourier transform of the time domain scans in the main panel. (f) Peak current (I) plotted as a function of V_g . (g) R as a function of V_g at 77 K. (h) Colorplot of I as a function of V_g and time at 77 K.

Upon cooling the circuit, we see enhanced effects of the p–n junctions. Figure 2(e) shows the transmission time domain scans for the CS circuit again but now at 77 K. A clear difference in the transient amplitude is discernible in the time domain and Fourier transform [inset of Fig. 2(e)] for two different gate voltages. The peak amplitude as a function of gate voltage is shown in Fig. 2(f) where the modulation now reaches 95%. A more dramatic asymmetry manifests in the gate dependent transport, with p-type carriers recording a higher resistance than n-type carriers. At $V_g = -4$ V, the graphene p–n junction has the highest resistance and therefore the largest transmission amplitude. At $V_g = 4$ V, the graphene p–n junction has the lowest resistance, and the transmission is nearly completely suppressed. A colorplot in Fig. 2(h) shows the readout current as a function of gate voltage and time delay contrasting the peak modulation in Fig. 2(d).

In the GW circuit, the modulation at low temperature is not as effective because the junction is better impedance matched to the waveguide (see Fig. S5). However, integrating the p–n junction directly into the center conductor affords the ability to control THz emission. This is demonstrated by incorporating a third beam, which directly excites the graphene

junction itself. Figure S6 in the [supplementary material](#) shows a schematic of this measurement where three beams and two delays are used to perform an on-chip pump-probe experiment. Figure 3(a) shows the DC characteristics of the GW circuit junction at 77 K. We again record a clear asymmetry in hole and electron transport from the p–n junction. Figure 3(b) shows a 2D plot of the readout current at the left PC switch vs the pump and transient time (TT) delays, taken at $V_g = 0$ V. There are three discernible features that run horizontally, vertically, and diagonally through the scan, which converge near the center of the plot. The highest recorded current occurs at this point when the on-chip transient pulse arrives at the graphene at the same time as the free-space pump pulse. The vertical and diagonal features correspond to the transient pulse and the pump induced change to the transient pulse, respectively.

We also identify a horizontal feature—i.e., a feature independent of the transient pulse—which we ascribe to emission from the graphene junction itself. Picosecond pulse emission has been previously studied in 2D materials including graphene,^{40–42} MoS₂,⁴³ and bismuth selenide (Bi₂Se₃).⁴⁴ In graphene, emission can occur as a result of photocurrents driven by an applied voltage⁴¹ or from the photothermoelectric effect, generated by current flow between closely spaced regions with

FIG. 3. Gate tunable emission in the GW circuit at 77 K. (a) DC resistance (R) as a function of gate voltage (V_g) at 77 K for the GW graphene p-n junction. (b) Colorplot of the readout current (I) as a function of the pump (pump time) and transient [transient time (TT)] time delay. The dashed line at $TT = -25$ ps corresponds to the linecuts shown in panels (c) and (d). (c) Readout current (I) as a function of pump time at $V_g = 0$ V and $TT = -25$ ps. (d) I as a function of pump time for two gate voltages, $V_g = -4, 4$ V at transient time $= -25$ ps. The top inset shows a colorplot of I vs V_g and pump time (time) for all gate voltages explored. Blue corresponds to low current and yellow to high.

dissimilar doping, with examples including both contact-induced⁴¹ and gate controlled p-n junctions.⁴² In our device, the graphene junction is grounded on both sides, so there is no applied voltage that would give rise to emission from a fast photoconductive mechanism. Instead, we see a direct correlation between the emission and the state of the p-n junction, suggesting that the emission mechanism is a result of a photothermal voltage from the photothermoelectric effect, which drives an ultrafast photocurrent across the junction. With access to both nnn and npn junctions at various gate voltages [Fig. 3(a)], we can effectively turn on and off the dissimilar doping interface and thereby control emission. Figure 3(c) shows the emission signal well before the arrival of the transient, corresponding to the dashed white line in Fig. 3(b).

At $V_g = 0$ V, the emission peak amplitude is weak as the center of the junction at charge neutrality, so that no sharp heterointerface is present to give rise to photothermoelectric currents. By tuning the gate voltage, however, the emission amplitude can be strongly enhanced. Figure 3(d) shows the time domain scan of the pump signal at $V_g = \pm 4$ V and $TT = -25$ ps. At $V_g = -4$ V, deep in the npn state, we record strong high frequency emission from the graphene junction. By tuning the junction into the nnn state, $V_g = 4$ V, the emission is suppressed. The inset of Fig. 3(d) shows the complete evolution of these time domain scans with gate voltage. Various heat dissipation channels through the substrate and contacts could contribute to the slower time response we record here when compared to ultrafast photothermoelectric signals observed in other junctions.⁴²

Summarizing, we investigated the potential of integrated graphene junctions in high frequency circuits to control the transmission and emission of THz transients on-chip. Our results reveal that 2D materials have strong potential in high frequency applications as tunable sources and modulators. The explored geometries additionally lend themselves to spectroscopic studies of nanomaterials with dimensions below the diffraction limit at THz frequencies.

See the [supplementary material](#) for the carrier relaxation times of the Si photoconductive switches, a description of the transient generation and detection measurement, details about p-n junction creation, mobilities, finite difference time domain simulations of the CS circuit, modulation characteristics of the GW circuit, and a description of the pump beam measurements.

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The data that support the findings of this study are available from the corresponding author upon reasonable request.

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