High Frequency Characteristics of Graphene Geometric Diodes

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Background

- Geometric diodes have the potential to provide ultra-fast rectification due to their low capacitance for a low RC time constant, and fast charge carrier transit times.
- Incorporated into rectennas, geometric diodes can be used for the efficient conversion of infrared signals into DC electrical power.
- **We present, for the first time, time-dependent simulations of graphene geometric diodes.**
- Frequency-dependent characteristics are determined and assessed in the context of the Drude model.

1. Geometric Diodes

- Planar structures with geometric asymmetry that yields a preferred direction for charge flow (current)
- Mean-free path length of charge carriers must be on the order of critical device dimensions
- Graphene is choice material with mean-free path lengths as high as 1 µm
- Inherently low capacitance and ballistic transport allow for ultrafast rectification, into IR frequencies
- Z-diode geometry exhibits enhanced rectification

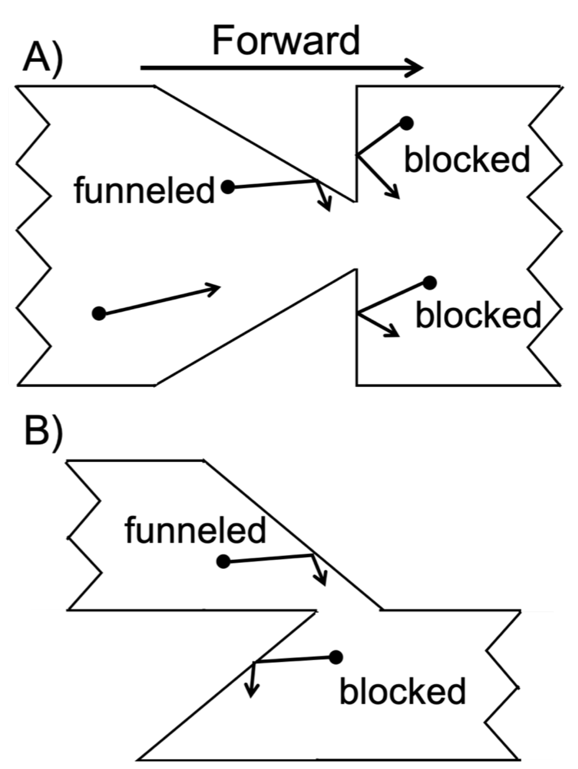

Fig. 1 Operating principle of geometric diode in two possible geometries: an arrowhead diode (A) and Z-diode (B). Electrons are guided through in the forward direction, but blocked in the reverse direction.

2. Simulation

Simulator consists of three components

1. Distribute lumped electron macro-particles in discretized space using a particle-in-cell* (PIC) algorithm
2. Solve Poisson's equation for electric field everywhere in device, with a voltage applied between left and right boundaries
3. Propagate charges over small time step, reflecting charges at devices edges and count charges that pass through either electrode boundary to derive current

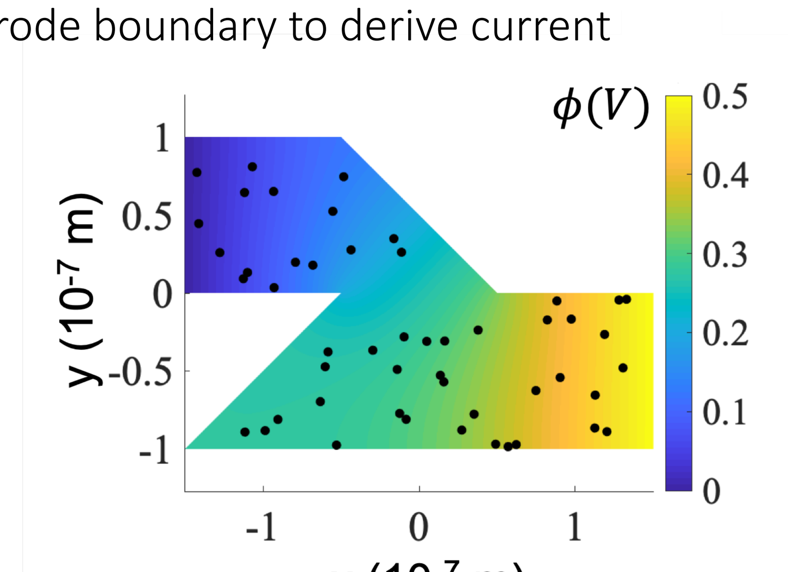

Fig. 2 Simulated potential, ϕ, in a graphene Z-diode immediately after 500 mV is applied. The ~100 nm dimensions are less than the mean-free path length of electrons in graphene. Black dots represent macro-particles in the PIC algorithm.

* D. Tskhakaya. *Lecture Notes in Phys.*, vol. 739, p. 161, (2008).

3. DC Diode Characteristics

- Geometric asymmetry in Z-diode gives rise to current-voltage asymmetry
- Asymmetry $= |I(V_{DC})/I(-V_{DC})|$ quantifies the strength of the diode behavior
- Asymmetries approaching 2 below 1 volt are substantial compared to other ultra-fast diodes

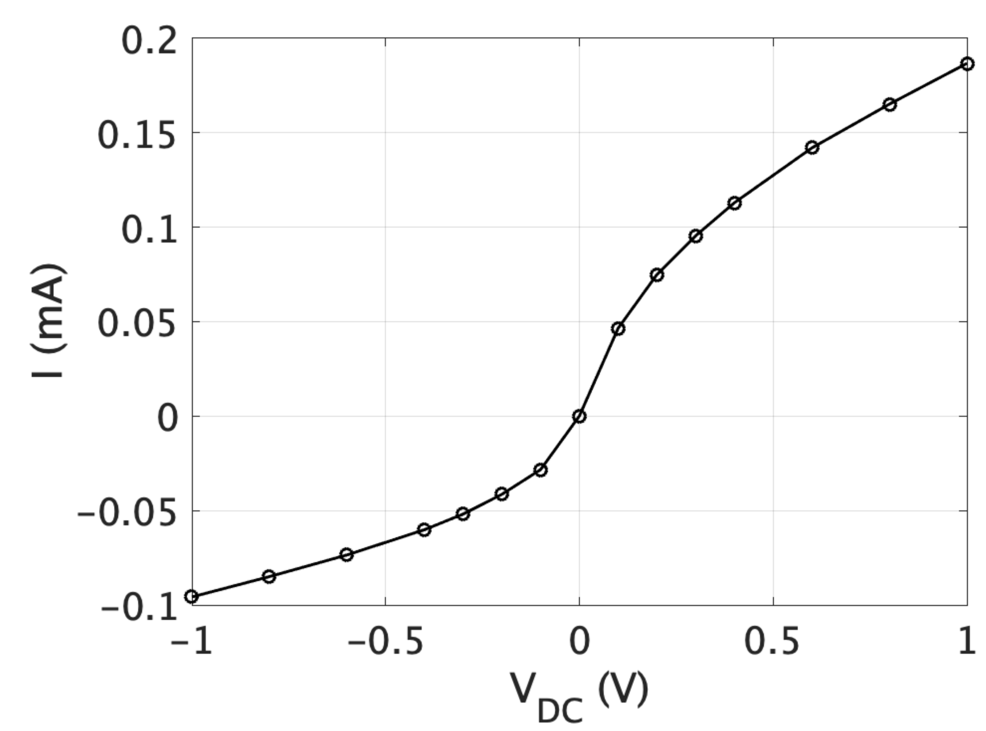

Fig. 3 Simulated DC current, *I* as a function of applied DC voltage, V_{DC}, for the Z-diode shown in Fig. 2.

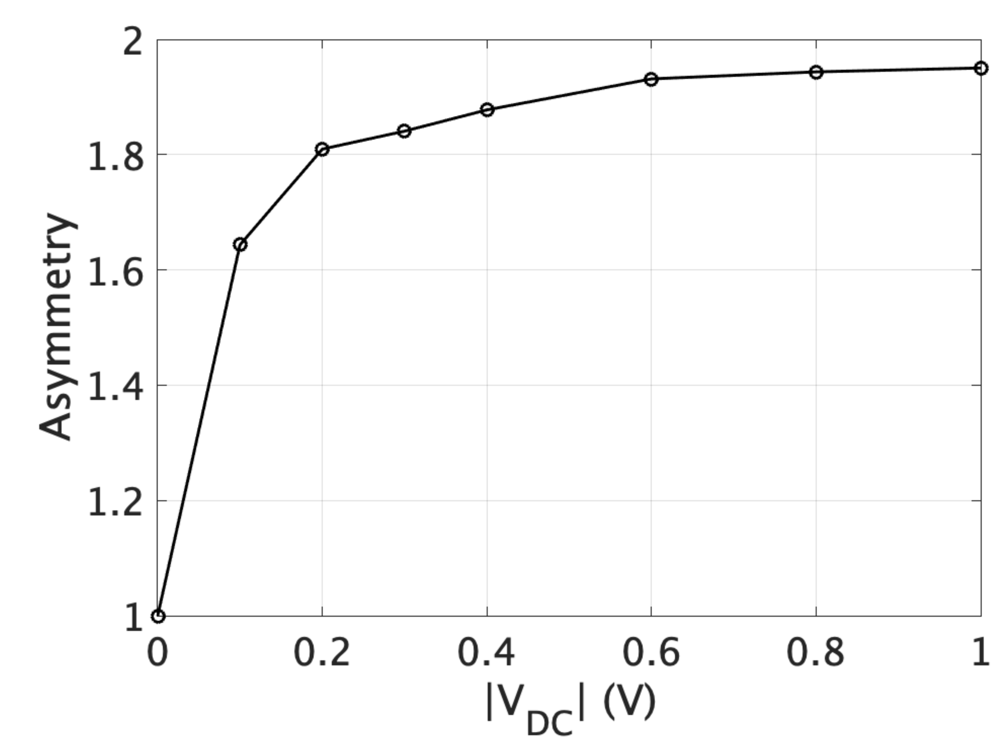

Fig. 4 Simulated DC current asymmetry for the Z-diode in Fig. 3

4. AC Diode Characteristics

- AC diode performance may differ from DC performance due to limitations in how fast charge carriers can move
- Rectification quantified by AC asymmetry, ratio of peak forward current to peak reverse current
- At higher frequencies, AC asymmetry is reduced, as is the overall current response of the diode (explained at right)
- Current response begins to lag the voltage input at high frequencies (explained at right)

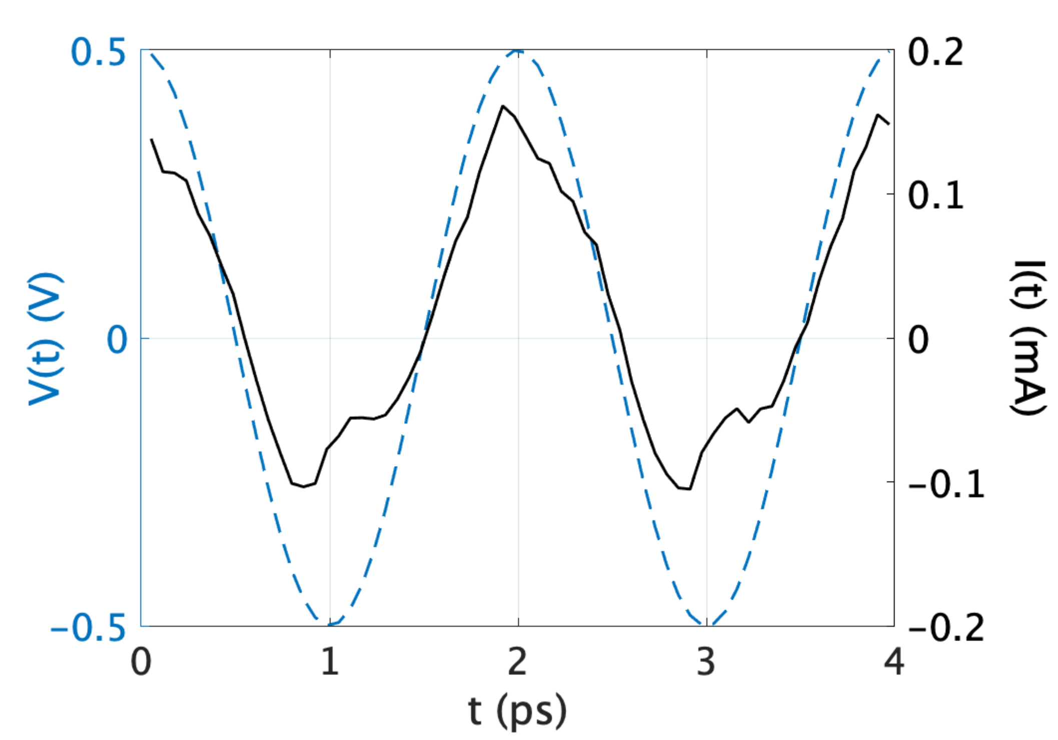

Fig. 5 Simulated time-dependent current (solid line) for a 500 mV input (dashed line) at 500 GHz for the diode in Fig. 3 and Fig. 4. Rectification manifests as the passage of more current in forward bias than reverse.

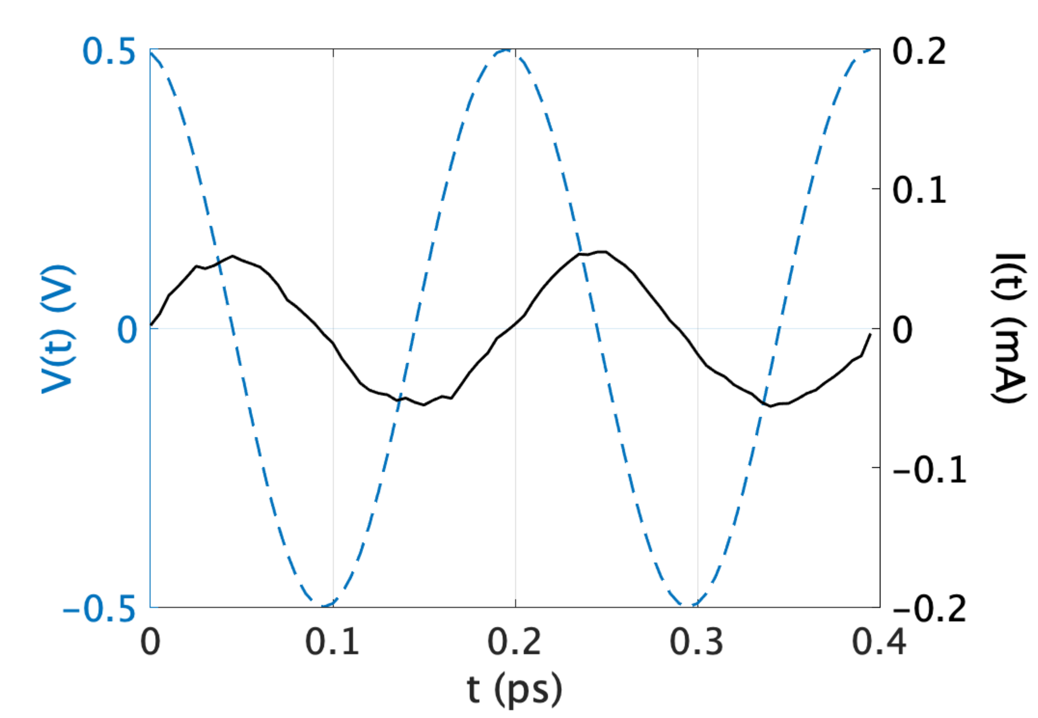

Fig. 6 Simulated time-dependent current (solid line) for a 500 mV input (dashed line) at 5 THz for the diode in Fig. 3 and Fig. 4. The current is lower and much more symmetric than the 500 GHz case, and a substantial lag is observed.

5. Frequency Dependence

- In simulation, asymmetry is reduced at high frequencies
- Above 5 THz, no rectification takes place

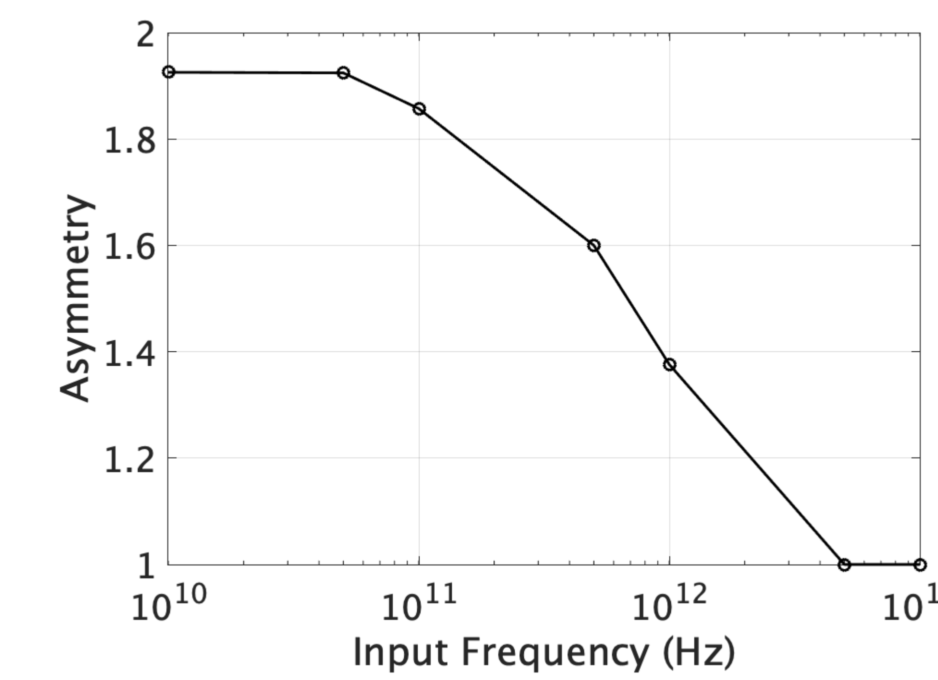

Fig. 7 AC current asymmetry at 500 mV as a function of frequency

- Drude model of conductivity, σ, takes form $\sigma \propto 1/(\gamma - i\omega)$, for radial frequency, ω, and collision frequency, γ
- For $\omega > \gamma$, $|\sigma|$ is reduced and phase delay is introduced as charges are slow to change direction without collisions (e.g. Fig. 6)
- As $|\sigma|$ decreases, less current flows and the rectification effect weakens
- Symmetric graphene strip simulated and $\sigma(\omega)$ calculated

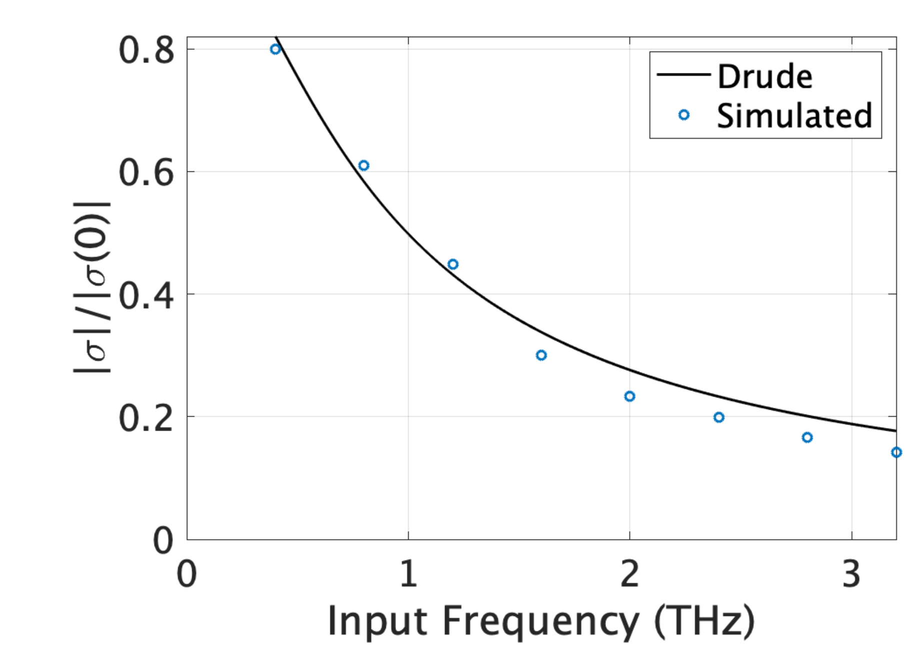

Fig. 8 Frequency-dependent conductivity of a rectangular graphene strip. Blue circles are derived from simulations, the black line is fit to $\sigma \propto 1/(\gamma - i\omega)$.

- Simulated conductivity fits closely to Drude model with $\gamma \approx 1$ THz
- Measured responses up to 28 THz have been observed*, likely due graphene's additional optical conductivity from interband transitions, not accounted for in simulation

* Z. Zhu *et al.*, *J. Phys. D: Appl. Phys.*, vol. 46, p. 185101, (2013).

Conclusions

- In simulation, graphene geometric diodes are predicted to rectify up to terahertz frequencies, making them an attractive technology for infrared energy conversion.
- The weakened response above 1 THz is found to be consistent with the Drude model of conductivity.
- In practice, interband transitions contribute to additional conductivity beyond 1 THz, which has been supported by previous measurements. These effects will be incorporated in the future.
- Optimization of the dimensions of the diode will lead to improvements in rectification efficiency.