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Ultra-Compact, Entirely Graphene-based Nonlinear Leaky Integrate-and-Fire Spiking Neuron

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Overview

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- Neuron Structure and Functionality
- Nonlinear Leaky Integrate-and-Fire Neuron model
- Basic Graphene-based Device
- Graphene-based Spiking Neuron Structure
- Simulation Framework
- Simulation Results
- Conclusions

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Motivation

Artificial spiking neurons are of particular interest:

- Artificial neurons are the basic components in neuromorphic systems.
- Spiking neurons are biologically plausible and energy-efficient.

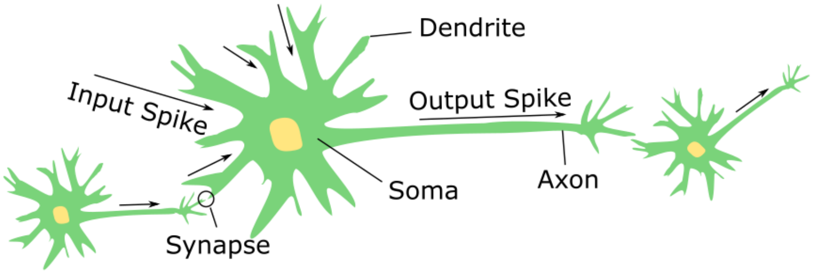
State-of-art artificial neurons (CMOS, resistive switching memory devices, phase-change devices, etc.) limitations:

- Scalability drawbacks (large energy consumption and area footprint)
- Variability-induced instability

Graphene merits:

- Outstanding properties, e.g., ballistic transport, ultimate thinness, an inherently analog nature, flexibility, biocompatibility.
- Previous work on graphene-based gates and artificial synapses demonstrated graphene’s potential for compact and energy efficient implementations.

Neuron Structure and Functionality



- Soma: the neuron’s cell body.
- Dendrites: connect the neuron with multiple other neurons.
- Axon: transmits the output spike to neighboring neuron.

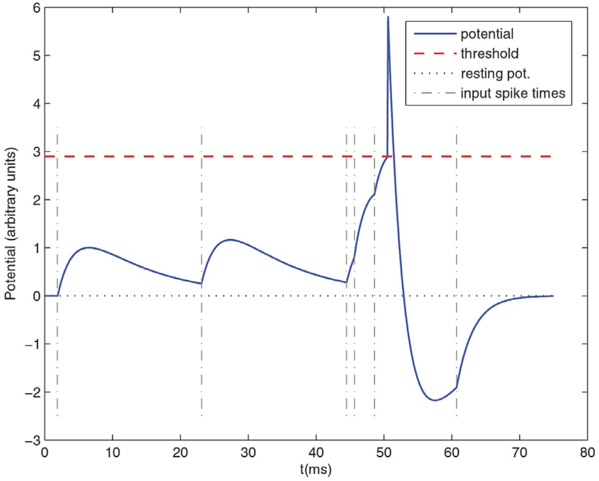
A neuron collects signals from multiple other neurons, and will generate an output spike when the accumulated signals exceed a certain threshold.

Nonlinear Leaky Integrate-and-Fire Neuron Model

Nonlinear Leaky Integrate-and-Fire neuron:

$$\frac{du}{dt} = F(u) + G(u) \cdot I$$

u: membrane potential
$F(u)$: voltage-dependent leak term
$G(u)$: voltage-dependent input resistance
I: input current



- Integration process.
- Firing event.
- Refractory interval.

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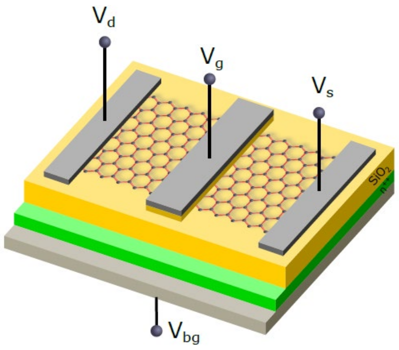
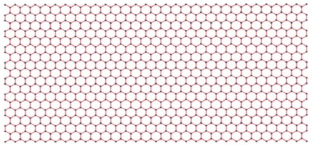
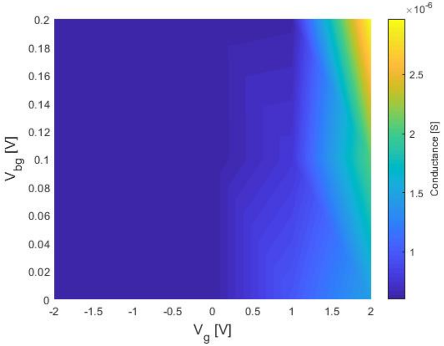
Basic Graphene-based Device



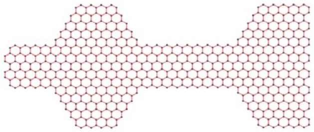
The Graphene Nanoribbon (GNR) conductance can be modulated by:

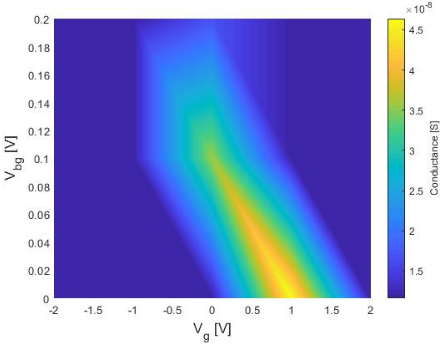
- changing the graphene sheet geometry and the contacts topology.
- external voltages via the top/back gates.





GNR conductance map



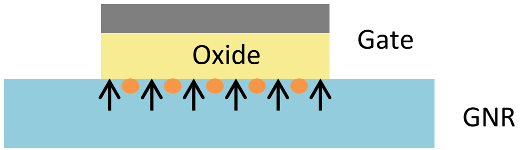


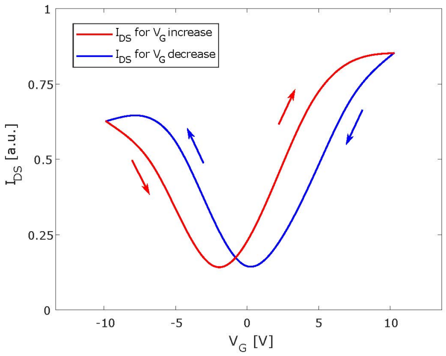
GNR conductance map

Basic Graphene-based Device

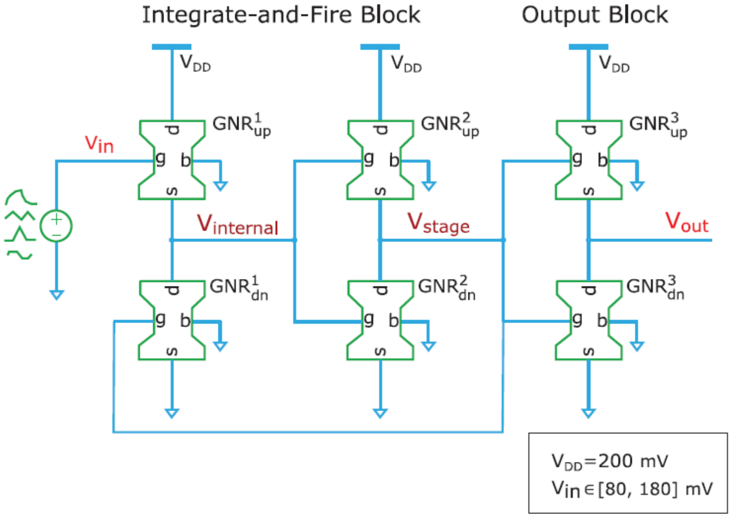
GNR device interface charge trapping/detrapping phenomena.

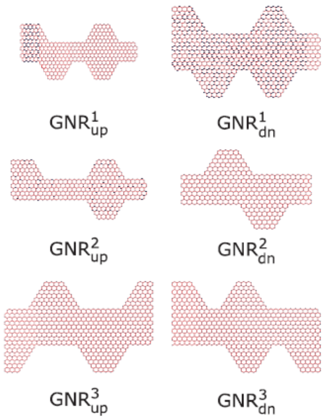
- It was experimentally observed that GNR devices inherently exhibit near-interface traps.
- The membrane potential integration features are naturally captured by the interface charge trapping/detrapping phenomena.

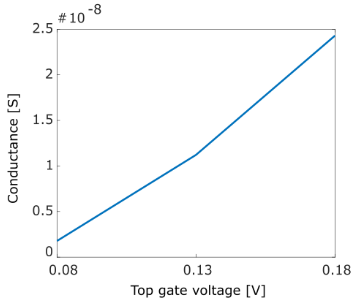




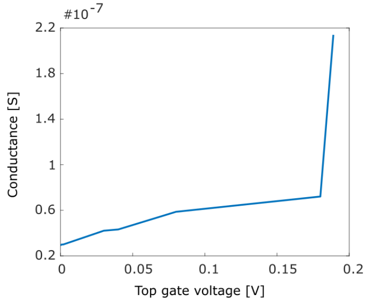
Graphene-based Spiking Neuron Structure







GNR^{1}_{UP} Conductance



GNR^{2}_{UP} Conductance

- Integrate-and-Fire block: Mimics the membrane potential dynamics.
- Output block: Generates the output spike.

Simulation Framework

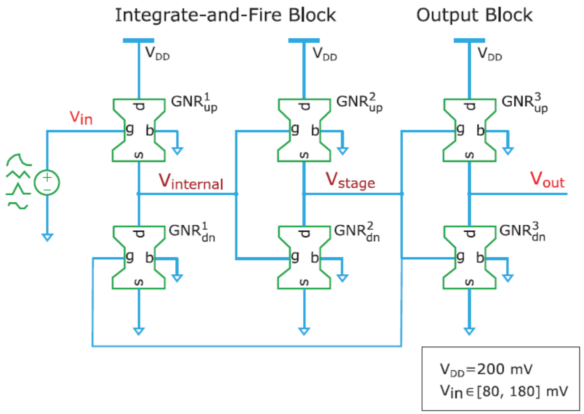
To model the graphene electronic transport properties: an atomistic-level traps-aware simulation model.

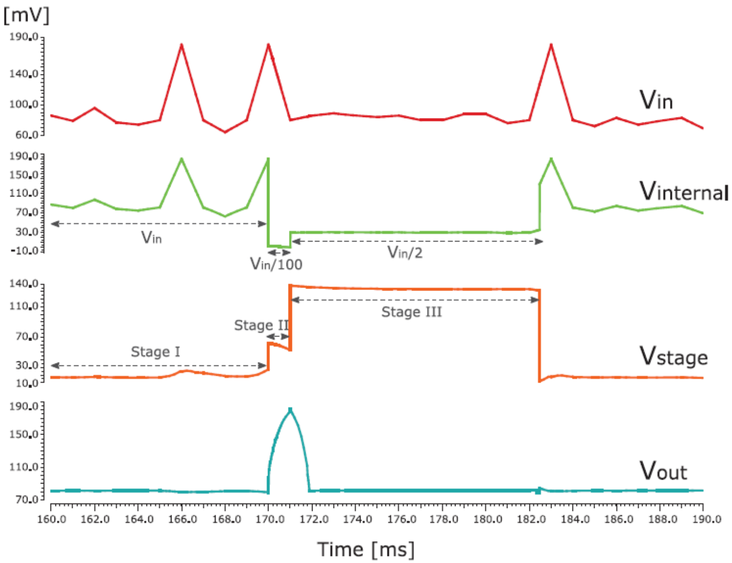
- Tight binding Hamiltonian: modelling the interactions between carbon atoms.
- Non-Equilibrium Green Function and + Landauer-Büttiker formula: modelling the transport properties.
- 3D Poisson Solver: Calculating the potential distribution on the graphene self-consistently.
- Traps induced hysteresis formalism: Calculating the voltage shift caused by interface traps.

To validate and evaluate the neuron circuit behavior: SPICE simulation in Synopsys HSPICE.

- A Verilog-A SPICE compatible generic model, which relies on look-up tables containing GNR behavior data.

Simulation Results

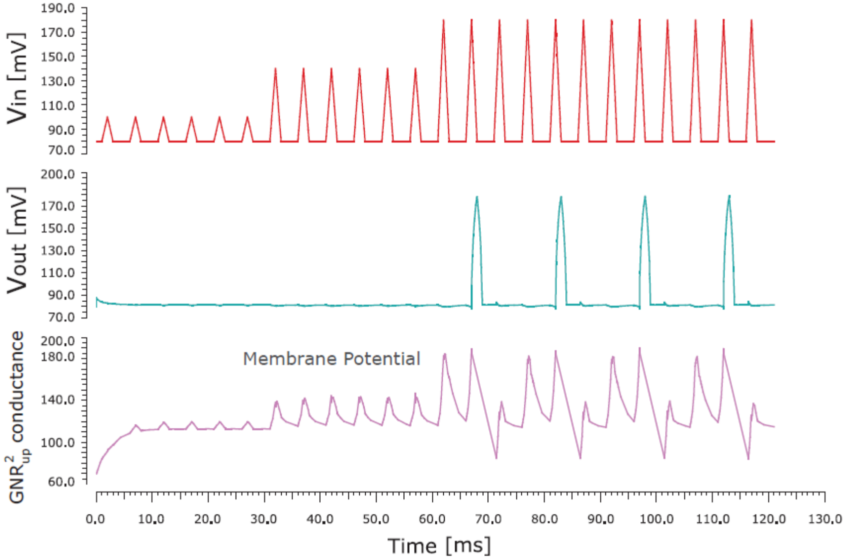


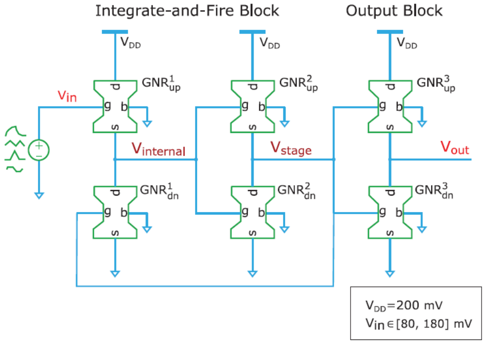


Basic operation.

- Stage I: integrate and fire.
- Stage II: reset the membrane potential and release the traps.
- Stage III: refractory interval.

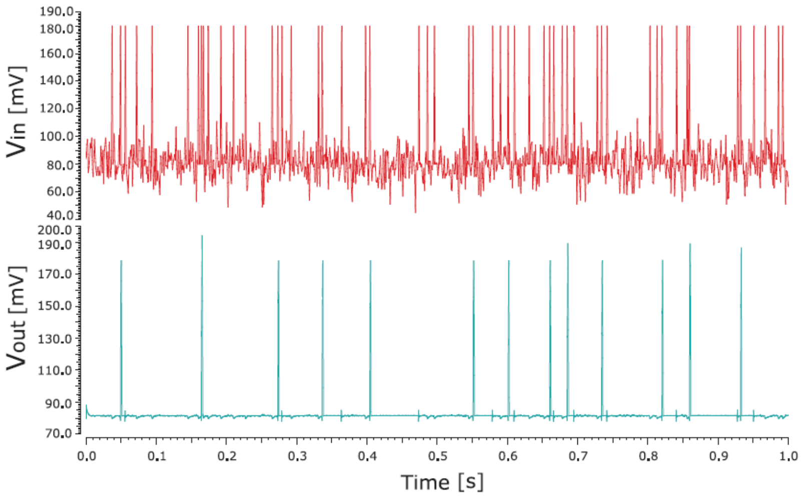
Simulation Results



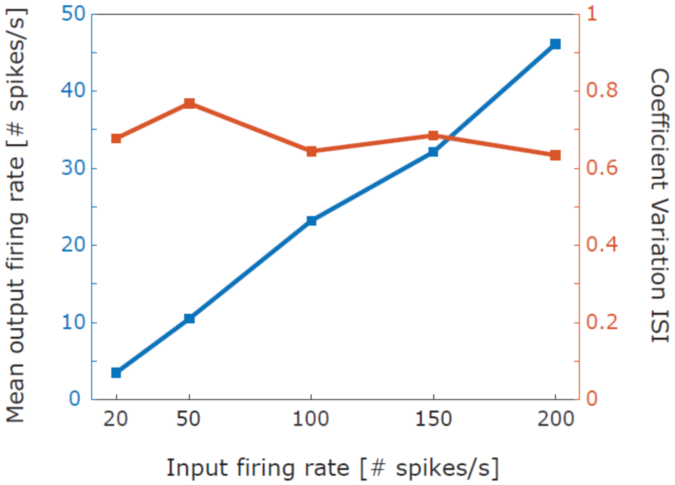


Integrate-and-fire dynamics with variable input spike peak amplitude.

Simulation Results



Graphene-based neuron dynamics under noisy random input.



Output spike statistics for variable input firing rate.

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Conclusions

- The proposed graphene-based neuron can properly emulate the basic spiking neuron dynamics.
- The proposed graphene-based neuron exhibits robustness under noisy input, and regularity of firing events under variable input firing rate.
- The small area, low energy and biologically plausible settings suggesting the proposed design a good candidate for large-scale biocompatible neural systems.

Thank You!

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