**Graphene Devices for Beyond-CMOS Heterogeneous Integration**

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Abstract

Semiconductor manufacturing is the workhorse for a wide range of industries. It lies at the heart of consumer electronics, telecommunication equipment and medical devices. Most semiconductor electronics are made from Silicon, and are fabricated using CMOS technology. The versatility of semiconductor electronics stems from the ever-reducing cost of integrating more computing and memory functions on chip. The small cost for adding extra functions has been maintained in the past 50 years through transistor scaling. Transistor scaling focuses on shrinking the size of transistors integrated on chip. This reduction in transistor size, while keeping the overall cost of the chip fixed allowed us to reduce the cost per function with scaling, and is what is celebrated as Moore’s law. Scaling has been working gracefully up to the last decade, where the exponential rise in manufacturing cost and diminishing gains of scaling on device performance reduce its economic benefit. To revive the cost reduction trend, different techniques were proposed such as augmenting CMOS manufacturing with new materials (Beyond CMOS), 3D integration, and integrating more non-transistor elements on-chip (More than Moore).

In this work, we focus on the efficient implementation of several circuit functions using an allotropy of carbon known as graphene. Graphene, a single layer of carbon atoms arranged in a hexagonal lattice, has unique electronic properties that has been taken the solid-state electronics community by a storm since its first experimental conception in 2004. Despite its promising electronic properties, namely the very high charge-carrier mobility and reduced scattering by impurities, graphene circuits has been held back by a plethora of nonidealities and technological roadblocks that hamper its use in traditional transistor-based circuits. In this work, we attempt to leverage the unique physical properties of graphene to implement non von-Neumann neuromorphic computing architectures, low-loss diodes and evaluate the behavior of diffusive-transport graphene couplers. We focus on the the design, fabrication and characterization of graphene devices in the presence of the current performance-limiting technological nonidealities in heterogeneous graphene-CMOS systems. We present the design, fabrication and characterization of all-graphene resistive data converters devices and diodes, discussing their performance and application as building elements of all-graphene brain-inspired computing architectures. We evaluate the performance of graphene couplers operating in the diffusive transport regime, which serve as a method to analyze the cross-coupling between adjacent graphene interconnects. We also discuss the current technological limitations hampering the performance of graphene devices, and the roles of different processing non-idealities on the characteristics of graphene devices.

Table of Contents

List of Tables

List of Figures

# Introduction

The Semiconductor Industry has evolved over the d

## Economics of Scaling and Moore’s Law

## Beyond-CMOS Materials and Devices

## Graphene as a Beyond-CMOS Material

## Overview of Document

# The Electronic Properties of Graphene

## Electronic Band Structure of Graphene

## Klein-Tunneling and the Absence of Backscattering

## The Role of the Substrate

## Charge Transport in CVD Graphene

## Contact-Induced Doping

## Characterization of Graphene

### Raman Analysis

### Constant Mobility Model

# All-Graphene Neuromorphic Computing Architectures

## Cellular Neural Networks (CNNs)

## All-Resistance CNNs

## Graphene Neurons and Synapses

## Measurement Results

## Conclusion

# Graphene Low-Loss Diodes

## Geometric Graphene Diodes

## Oblique Incidence Diodes

## Performance Limitations

### Lead Resistance

### Momentum Distribution Smearing by Scattering

## Measurement Results

## Conclusion

# Diffusive-Transport Graphene Couplers

The similarity between the dispersion relation of photons and charge carriers in graphene appeals to designing optics-inspired electronic devices. An interesting optics-inspired analog is the electronic directional coupler. Optics directional couplers allow coupling light between two branches, where the coupling coefficient varies periodically with the coupling distance[1]. The electronic wave modes in graphene ribbons and the resistive coupling between graphene ribbons in close proximity has been analyzed for ballistic transport [2]–[4]. The problem of analyzing resistive coupling in diffusive graphene ribbons is different from that in ballistic graphene ribbons. The successive scattering events randomize the wavefunction phase information [5]–[7] prohibiting the direct application of the coupled-mode theory. A direct consequence of this phase randomization is losing the spatial periodicity of the coupling coefficient predicted in ballistic devices.

Modeling of resistive coupling is also crucial for deeply scaled interconnects, in which transport will inadvertently be diffusive due to line-edge roughness[8]–[10]. Graphene interconnects in close proximity has been studied previously to evaluate their cross-talk performance[11]–[17]. Prior work focused on analyzing the delay and energy metrics of a single graphene interconnect, accounting only for the capacitive coupling among interconnects.

In this chapter, we study the coupling between graphene ribbons operating in the diffusive transport regime. We start by developing an analytical model for the coupling resistance between two graphene ribbons separated by a dielectric, highlighting the impact of different fabrication nonidealities on the coupling. We then evaluate the spatial dependence of such coupling coefficient, showing its monotonic saturating behavior, and assess the impact of such coupling on the performance of deeply scaled interconnects.

## Modeling Diffusive-Transport Current Coupling

An electronic current coupler consists of two graphene ribbons in close proximity as shown in Figure 1. The phase incoherence associated with diffusive transport devices prohibits the direct application of coupled mode theory to evaluate the coupling between two coupled graphene ribbons. A more direct approach would be to model the coupling using the tunneling resistance between the two branches of the coupler; this emphasizes the diffusive nature of the transport and the lack of phase coherency in the associated wave functions.

The modeling of the tunneling resistance between the two graphene ribbons must take into account the difference in energy dispersion relations across the tunneling barrier. The energy dispersion relation of charge carriers changes from a linear dispersion relation in graphene, to a parabolic dispersion relation with an energy gap in the oxide regions, as shown in Figure 2. The lack of states in the dielectric energy gap translates to decaying wavefunctions from the graphene ribbons on either side of the dielectric. In other words, despite the linear energy dispersion relation of graphene, the lack of states in energy gap region of the parabolic dielectric gives rise to a decaying wavefunction, reminiscent of tunneling in parabolic systems.

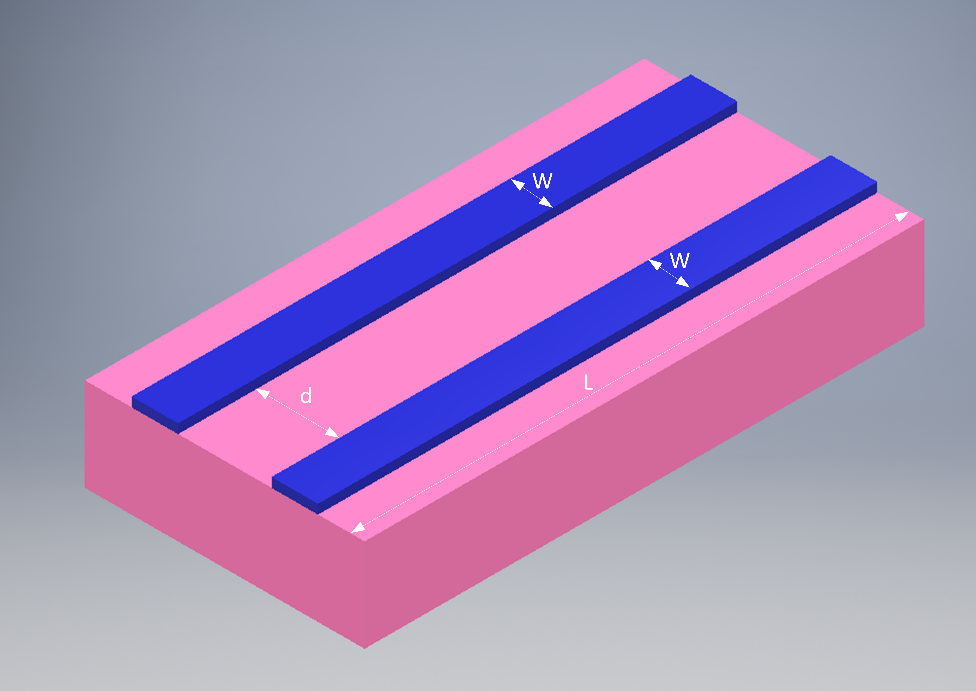


Figure ‎5.1 Schematic representation of an electronic graphene coupler. The ribbons are spaced by a distance d apart, over a length of L, while each ribbon has a width of W. The graphene is shown in blue while the surrounding oxide is shown in pink. The oxide is only shown below the graphene ribbon for clarity.

The calculation of the tunneling resistance is based on the analysis of Graphene-Insulator-Graphene (GIG) junctions[18], [19]. The major difference between the prior work on GIG junctions and the current problem is that in this device tunneling occurs between the edges of the graphene ribbons rather than normal to them. The edge tunneling nature modifies the results presented in [18], [19] slightly, but follows its essence otherwise. We defer the estimation of the tunneling resistance to Section ‎5.1.1, but stress on the fact that it is a tunneling resistance; its value is limited by how small the two ribbons can be spaced apart, and for all practical purposes, this tunneling resistance value is significantly larger than the resistance of the graphene ribbons. This observation will proof useful when analyzing the electrical model of the device.

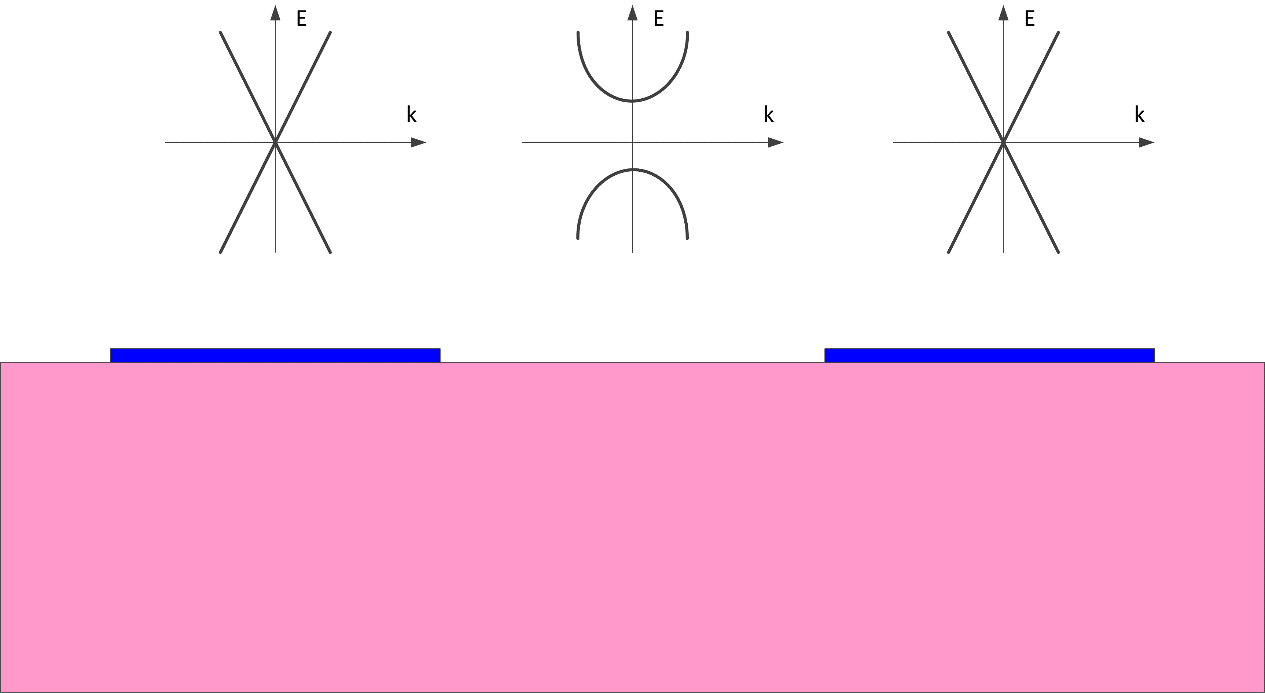


Figure ‎5.2 Cross Section of the graphene coupler with the bottom oxide only shown for clarity. The electronic energy dispersion relation for each region is shown above it; it is linear in each graphene region and parabolic with a band gap in the dielectric surrounding them. The energy gap in the parabolic region is significantly larger than the energy of charge carriers in each graphene ribbon.

The electrical model of the device is composed of three distributed resistors: a distributed resistor for each of the graphene ribbons with a distributed tunneling conductance connecting them together, as shown in Figure 3. We label one of the ribbons as the input ribbon, and the other as the output ribbon. For this analysis, we apply a current stimulus at the input ribbon and calculate the current at other end (output) of each ribbon.



Figure ‎5.3 Electrical model of graphene coupler. The graphene ribbons are modelled using two distributed resistors with a resistance per unit length of R1 and R2, and the tunneling resistance coupling them is modelled using a distributed conductance with conductance per unit length gc.

The coupling coefficient between the current in the two ribbons is defined as the ratio between the output ribbon and input ribbon branch currents as:

|  |  |  |
| --- | --- | --- |
|  |  | (‎5.6) |

A detailed analysis of the electrical model is provided in ‎Appendix E. The current distribution and coupling are a strong function of the load at the output of each branch. This is expected due to the passive nature of the device that does not provide any buffering.

A closer look at the functional form of the voltage and current equations, boundary conditions and current conservation requirement reveals interesting information regarding the asymptotic behavior of the coupler.

### Estimation of the tunneling resistance

## Dependence Current Coupling Coefficient on Coupling Distance

## Impact of Current Coupling on Deeply Scaled Interconnects

## Conclusion

# Current Technological Limitations on Graphene Devices and Circuits

## Contact Engineering

### Electrical Resistance

### Thermal Interface Conductance

## Interface Roughness

## Stress in dual-gated Graphene FETs during Processing

## Impact of Metal-Ion Containing Developers on the Performance of Graphene FETs

# Conclusion and Future Work

## Alloyed Contacts for Optimized Thermal and Electrical Contact Resistance

## CVD Graphene over CVD hBN

## Mixing 2D Materials for Optimized Contacts

References

# Graphene Processing

## Preprocessing Anneal

## Photolithography

## Electron-Beam Lithography

## Electron-Beam Evaporation

## Top Gate Oxide/Passivation Deposition

# Fabrication of a Dual-Gated Graphene FET

# Measurement Setup for Dual-Gated Graphene FETs

# Measurement Setup for Graphene Diodes

# Derivation of the Current Coupling Coefficient in a Diffusive-Transport Graphene Coupler



Figure ‎E.1 Electrical model of graphene coupler. The graphene ribbons are modelled using two distributed resistors with a resistance per unit length of R1 and R2, and the tunneling resistance coupling them is modelled using a distributed conductance with conductance per unit length gc.

The electrical model of the device is composed of three distributed resistors: a distributed resistor for each of the graphene ribbons with a distributed tunneling conductance connecting them together, as shown in Figure 3. We label one of the ribbons as the input ribbon, and the other as the output ribbon. For this analysis, we apply a current stimulus at the input ribbon and calculate the current at other end (output) of each ribbon.

We start by solving the voltage differential equation for the distributed system then relating it to the current.

Applying KCL at any node the node (i), we get:

This can be rewritten as:

Taking the limit as , we get:

Substituting from the two equations together to decouple the equations we get:

Accordingly, the differential equation for each branch after substitution:

The resulting decoupled equations are:

|  |  |  |
| --- | --- | --- |
|  |  | (‎E.1) |

|  |  |  |
| --- | --- | --- |
|  |  | (‎E.2) |

The two differential equations are the same. The general solution is written as:

|  |  |  |
| --- | --- | --- |
|  |  | (‎E.3) |

The above equation can be rewritten by setting to be:

|  |  |  |
| --- | --- | --- |
|  |  | (‎E.4) |

Current conservation dictates the boundary conditions on the current as:

|  |  |  |
| --- | --- | --- |
|  |  | (‎E.5) |

KCL relates the current and voltage at any given position as:

|  |  |  |
| --- | --- | --- |
|  |  | (‎E.6) |

In addition, Ohm’s law as relates the voltage and current at the output end of each ribbon:

|  |  |  |
| --- | --- | --- |
|  |  | (‎E.7) |

The coupling coefficient between the current in the two ribbons is defined as the ratio between the output ribbon and input ribbon branch currents as:

|  |  |  |
| --- | --- | --- |
|  |  | (‎E.8) |

The right side of Equation (‎E.5) can be solved for the relation between the constant to give:

|  |  |  |
| --- | --- | --- |
|  |  | (‎E.9) |

By letting , we can write the current in each branch using the left side of Equation (‎E.5) as:

|  |  |  |
| --- | --- | --- |
|  |  | (‎E.10) |

Applying KVL across each branch of the coupler, we have the KVL equations:

|  |  |  |
| --- | --- | --- |
|  |  | (‎E.11) |

This yields a relation between , and allows reducing (‎E.10) to:

|  |  |  |
| --- | --- | --- |
|  |  | (.) |

Equation (‎E.12) is reveals the behavior of the current coupler: The current is initially distributed according to the ratio of the two ribbons resistance per unit length, then the current starts to change due to the coupling tunneling resistance.

The voltage across each ribbon is this given as:

|  |  |  |
| --- | --- | --- |
|  |  | (.) |