Second Edition

CURRENT AT THE NANOSCALE

An Introduction to Nanoelectronics

Colm Durkan

World Scientific

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An Introduction to Nanoelectronics

For Biddy, Ben & Rosie

Preface to Second Edition

Since the first edition of this text came out in 2007, a lot has changed in the world of nanotechnology. Some topics have borne fruit and others have not. The underpinning science remains the same, so the overall thrust of the text is unchanged, but has been enhanced by going into more detail wherever necessary. In particular, a section has been added on a primer in quantum mechanics, more details have been added about scanning probe microscopy (my primary research interest), and further details have been added about metal nanowires and molecular electronics, with some new experimental data of interest.

We are in an age where, in the Western world at least, we all take high technology pretty much for granted. Many of us use and even depend on mobile phones, laptops, PDAs and other miniature electronic devices during our daily lives. What has made this all possible are advances in semiconductor technology, at the centre of which is the humble transistor. Next to the discovery of penicillin, the invention of the solid-state transistor was arguably one of the most important developments for mankind over the past century, as it has had far-reaching consequences across all aspects of life.

As the scale of electronic devices continues to decrease, and approaches the nm level, it is becoming more and more important to understand the details of current flow in reduced dimensions. This book is intended as an introductory overview of transport phenomena from the macroscale right down to the atomic level. There are two means by which nm-scale devices can be fabricated — by top-down or bottom-up technologies. The top-down approach has been used with obvious success by the semiconductor industry for several decades now and the bottom-up approach is being pioneered by researchers in the field of nanotechnology. Whilst current indications are that bottom-up nanotechnologies will not completely replace top-down technologies, the two will almost certainly become complementary. In any event, it will still be essential to have a sound understanding of transport at the nanoscale. We begin in Chapter 1 by looking at transport in familiar devices: resistors and transistors, and how, despite any ideas we may have to the contrary, their electrical characteristics are determined by events at the quantum level. To aid this, there is a section on quantum mechanics and how it is relevant to understanding the electrical properties of materials. We then dedicate Chapter 2 to gaining a practical understanding of the quantum nature of current flow, i.e. the relationship between current and voltage and the origins of electrical resistance. In Chapter 3, we look at the boundary between the quantum and macroscopic regimes — known as the *mesoscopic* regime, and look at how geometry, size and microstructure start to play an important role in determining resistance at the nanoscale. In Chapter 4, we look at the techniques used to probe the electrical properties of structures and devices at the nanoscale — scanning probe microscopy. In fact, it was the development of scanning probe microscopes that jump-started the field of nanotechnology. In Chapter 5, we look at some of the detrimental effects of current flow: heating and electromigration in nanowires. This is particularly important due to the fact that while transistors in microprocessors continue to shrink, so too must the interconnects which join them together. The resilience of small wires to the flow of current for prolonged periods is not the same as for large (i.e. micron-scale) wires. In the final chapter, we take a look at the field of molecular electronics, which has gained a lot of interest in recent years due to the promise it holds for novel circuit functions. This text is intended to serve as a useful introduction to quantum mechanics, scanning-probe microscopy and electronic transport.

C. Durkan
Cambridge, June 2013

Preface to First Edition

We are in an age where, in the Western world at least, we all take high technology pretty much for granted. Many of us use and even depend on mobile phones, laptops, PDAs and other miniature electronic devices during our daily lives. What has made this all possible are advances in semiconductor technology, at the centre of which is the humble transistor. Next to the discovery of penicillin, the invention of the solid-state transistor was arguably one of the most important developments for mankind over the past century, as it has had far-reaching consequences across all aspects of life.

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C. Durkan
Cambridge, January 2007

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Chapter 1

Macroscopic Current Flow

Nanotechnology has been a topic arousing much interest for over a decade now, and is starting to deliver on its initial promise. The reason for this sustained interest is that when materials have features that are only a few nm across (a nm is one nanometer which is 1 billionth of a meter, and Nano comes from the Greek "Nanos", meaning dwarf), their physical (electrical, magnetic, mechanical, optical and chemical) properties start to become very sensitive to size and shape and can to a large extent be controlled, to create novel functionality. Transistors are already at the scale of ~ 20 nm, and are starting to display electrical characteristics that deviate from their classically expected ones — hence the need for this book.

In order to be able to gain any insight into current flow at the nanometer scale, which we will refer to from now on as the *nanoscale*, we must first consider what happens at *macro*scopic scales and then see the effect of reducing the dimensions to the *nano*scale. The behaviour of conventional electrical circuits can be understood in quite simple terms, whereas at the nanoscale, there are a number of subtle effects that can only be understood within the framework of quantum mechanics, as we shall see in this chapter and in Chapter 2. In between these disparate regimes, we have *mesoscopic* transport, which we will briefly consider in Chapter 3.

On the basis of his detailed experimental observations in the 1820s, Georg Ohm formulated his well-known law [1] stating the following:

For a constant temperature, the current flowing through a conductor is directly proportional to the potential difference between its ends. Or, $V = IR$.

This is illustrated in Fig. 1.1. The constant of proportionality between applied voltage and the resulting current is known as resistance, R. The resistance depends on the geometry of the conductor and a material constant — resistivity as $R = \rho l/A$, where l and A are the length and cross-sectional area of the conductor, respectively. As we will see later, when any of the dimensions of a conductor are shrunk to the nanoscale, resistivity itself becomes strongly dependent on geometry, and is no longer just a number. For now however, let us consider Ohm's law in more detail, from a purely classical (i.e. non-quantum) standpoint — Drude's model of electronic conduction.

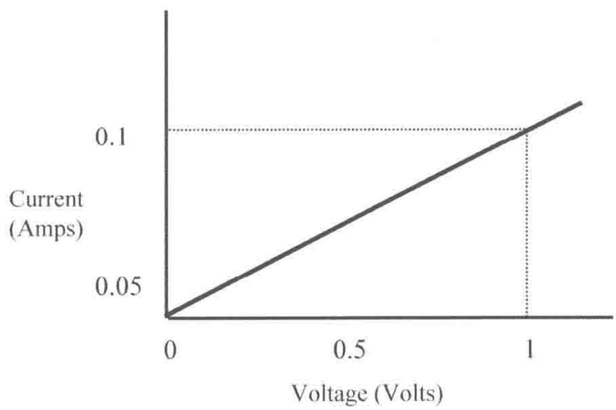

Fig. 1.1. Relationship between current and voltage for a conductor. In this case the resistance is 10 Ω (i.e. $V = 10I$).

We will then introduce the necessary corrections that must be made to be consistent with quantum mechanics which comes to the fore at small length scales. We will consider the following questions central to the flow of electric current:

1. What is electric current?
2. Why and how does current depend on voltage?