From nanoscience to nanometrology and its impact on electrical metrology

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Abstract

Metrology is often the first application of novel new science. For example the discovery of the Josephson effect transformed voltage metrology and the discovery of laser-cooling did the same for time & frequency metrology. The application of nanotechnology to electrical metrology has been going on for several decades. First there was the quantum Hall effect discovered in semiconductor heterostructures and now a lot of research is underway to harness single electron transport in nanoscale devices. Beyond this one can envision small portable quantum standards based on nanoscience which could bring un-paralleled accuracy outside the traditional specialised laboratories.

1. Introduction

How far can one shrink the electrical components in a computer chip? Electrical properties such as resistance and capacitance change dramatically when devices get smaller and smaller. The quantum nature of electrons will become apparent when the critical dimensions of a device are of a similar order as the electron wavelength. In semiconductor materials this can be of the order of a 100 nm or smaller. These quantum effects can have a negative impact on the operation of such devices and even prevent further miniaturization. An example is the leakage current (the result of electron tunneling) through the transistor gate which leads to excessive heating of the CPU chip. In order to tackle these problems the semiconductor industry has to use more and more advanced techniques and materials to continue the scaling down of CMOS technology, i.e. Moore's Law, at an ever-increasing cost. This traditional scaling process is predicted to end sometime in the next decade, beyond which novel disruptive technologies will have to be applied.

On the other hand quantum effects are a unique resource which can be exploited to our benefit. One of the simplest nanoscale quantum devices is the high mobility transistor which is based on a quantum well at the atomically sharp interface between GaAs and GaAlAs. The electrons are confined to a very narrow layer and form a so-called 2 dimensional electron gas. Such devices find particle applications in high-frequency amplifiers and multiplexers. When placed in a strong perpendicular magnetic field, plateaus are observed in the Hall resistance at values corresponding to h/ne^2 (here e is the electron charge, h is the Planck constant and n a positive integer). Interestingly, the Hall resistance only dependent on fundamental constants of nature and not on material or dimensional parameters. This is ideal for metrology because such a standard for resistance can be reproduced anywhere at anytime by anyone. The accuracy is only limited by our own measurement capability. Over the last three decades, the quantum Hall effect has revolutionized resistance metrology and all its derived units.

In nanoscale devices, size quantization, charge quantization and tunneling allow one to control the electron movement very precisely; down to the individual electron level. In particular much research is focused on devices which clock a known number electrons through a circuit. This will lead to a standards for electrical current with, $I=ef$, where e is the electron charge and f the clock frequency. Such a quantum standard could eventually replace the familiar definition of current via ampere's law which is impossible to realize in practice with great precision. Given that the electron charge is very small, a key objective in this research is to make the clock frequency as large as possible (on the order of GHz) in order to achieve a measurable current. All the base units in the International System of Units (SI) can in principle be defined in terms of fundamental constants and a large international effort is ongoing to achieve this by redefining the kilogram, ampere and kelvin, possibly as soon as 2015.

In nanoelectronic devices the energy scale is typically on the order of meV's which in terms of frequency is in the GHz to THz region of the spectrum. THz radiation is in an interesting and underdeveloped range of the electromagnetic spectrum with applications in security and biotechnology. A number of applications are starting to emerge where nanoscale devices are being investigated as extremely sensitive sensors for this radiation capable of detecting light at the single photon level.

Finally carbon is one of the most exciting materials of the last few decades. Carbon nanotubes and the recently discovered single atomic layer of graphene have been shown to exhibit an array of quantum effects even at room temperature. In particular graphene exhibits a novel electronic band structure which leads to a number of unique properties. One could envision developing these into to transportable quantum standards which would accessible outside specialized low temperature laboratories.

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