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Graphene on cubic-SiC

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ABSTRACT

The outstanding properties of graphene make it a top candidate for replacing silicon in future electronic devices. However, for technological applications, graphene must be synthesized on the surface of wide-gap semiconductors. In this review, we focus on graphene synthesized on single-crystalline cubic-SiC thin films epitaxially grown on standard silicon wafers. These low-cost substrates are commercially available and fully compatible with existing silicon technologies. The results obtained in recent years demonstrate that few-layer graphene synthesized on cubic-SiC substrates possesses the atomic structure and electronic properties of quasi-free-standing graphene. However, according to data obtained by various techniques, few-layer graphene on cubic-SiC consists of nanodomains connected to one another through nanodomain boundaries. After optimization of the preparation procedures, such a nanostructured graphene overlayer can represent a very promising system for the development of new graphene-based electronic devices. In particular, recent works demonstrate that continuous few-layer graphene with self-aligned nanodomain boundaries can be synthesized on vicinal SiC(001) substrates. Electrical measurements show the opening of a transport gap in nanostructured trilayer graphene synthesized on SiC/2°-off Si(001) wafers. This development may lead to new tunable electronic nanostructures made from graphene on cubic-SiC, opening up opportunities for a wide range of applications.

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1. Introduction

Graphene, a single layer of sp^2-bonded carbon atoms arranged in a honeycomb lattice, has attracted a lot of interest in recent years because of its astonishing electronic properties [1–6], which are very appealing for fundamental research and potential applications in electronic and photonic devices. The linear electron spectrum of graphene, which is related to the symmetry of its two-dimensional (2D) crystal lattice [7], was theoretically studied decades ago [8,9]. However, interest in graphene increased dramatically in the 2000s after successful practical exfoliation of this ultrathin carbon sheet [1]. Since 2004, many papers demonstrating unique physical properties of graphene, unusual quantum size effects, experimentally observed even at room temperature, and possible applications of the thinnest carbon-based 2D material have been published. For example, perspectives of technological applications in photosensors, transparent electrical contacts, and memory cells have been discussed in recent years [10–17]. Mechanically, graphene is the strongest material ever measured. The stiffness of graphene exceeds that of steel [18] and can be only slightly reduced in polycrystalline graphene having a large number of grain boundaries [19]. This can be utilized for a variety of applications, such as flexible electronics, strengthening components, and protective coatings [20,21]. Graphene has very high thermal conductivity exceeding that of the best bulk crystalline thermal conductors (*e.g.*, diamond and silicon carbide) [22,23] which is highly beneficial for thermal management and possible applications in photonic, electronic and magnetic storage devices having nanometer-sized elements. Due to its unique electron transport properties [24], graphene can be considered a top candidate for replacing silicon in traditional electronic technologies. Extremely high electron mean free path and mobility in graphene [1] make it especially promising in high-temperature and high-frequency electronic applications demanding both enhanced stability of the crystal lattice and high electron mobility. The absence of the band energy gap in pristine graphene can be overcome using active adsorbates [25] and nanopatterning [26–32]. The band gap in nanostructured graphene can additionally be tuned by mechanical strain applied to the nanoribbons [33,34] opening opportunities for development of logical elements based on graphene. Unsurpassed large spin relaxation times and diffusion lengths exceeding 100 μm make graphene a highly promising material for future spintronic applications [35–42]. Recently, several graphene-based spin-logic devices have been proposed [43,44]. Magnetic moments in graphene have been created using vacancy defects [45–48], doping with molecules or elements with large spin–orbital interaction [49–52], coupling with substrates [53,54], ripples and edges at domain boundaries [55–59]. Introducing the spin degree of freedom can lead to development of novel graphene-based spintronic devices, such as spin transistors or spin switches, as well as demonstration of exotic physical properties in atomic scale objects.

Strictly speaking, the word "graphene" refers only to a free-standing monolayer of carbon atoms (Fig. 1(a) and (b)). However, the term "graphene" is often applied in literature to bilayer and few-layer graphene, or even to ultrathin graphite multilayers stacked in a particular order (Fig. 1(c)). These forms can be considered special kinds of 2D crystals [2] with interesting properties. However, for successful electronic applications, single- or few-layer graphene sheets must be synthesized on semiconducting or insulating substrates. This review focuses on the synthesis and characterization of single- and few-layer graphene on cubic-silicon carbide (SiC) wafers suitable for electronic technologies. After a short description of different approaches to graphene synthesis and methods of growth of cubic-SiC single-crystalline thin films on standard silicon wafers, we will discuss the atomic and electronic structure and transport properties of few-layer graphene synthesized on various low-index and vicinal cubic-SiC substrates.

2. Methods of graphene fabrication

Historically, the first successful experiments demonstrating the unique properties of single-layer graphene were performed on ultrathin carbon sheets mechanically or chemically exfoliated from bulk graphite crystals [1,60–63]. Although these methods are hardly compatible with mass production, they could provide highest-quality samples for experimental studies of unusual 2D effects, even at elevated temperatures, and fabrication of singular prototype devices [6,64]. For example, the exceptional properties of 2D electron gas and extremely high charge carrier mobility in single-layer graphene were experimentally demonstrated for the first time in studies of ultrathin graphite flakes mechanically exfoliated from highly oriented pyrolytic graphite (HOPG) crystals and placed onto oxidized silicon wafers [5,6]. Nevertheless, the small size of the graphene sheets and the necessity of manipulating micrometre-scaled flakes in isolation from one another prevent the utilization of this method for the mass production of graphene compatible with electronic technologies.

More promising ways of single- and few-layer graphene fabrication could be based on the carbonization of metallic and semiconducting surfaces in a special environment (in vacuum or an atmosphere of different gases). Graphitization of single-crystal metal surfaces at specific conditions was observed in the 1960s, when the formation of ultrathin graphite films was