Device applications of epitaxial graphene on silicon carbide

M. Beshkova, Lars Hultman and Rositsa Yakimova

Linköping University Post Print

N.B.: When citing this work, cite the original article.

Original Publication:

M. Beshkova, Lars Hultman and Rositsa Yakimova, Device applications of epitaxial graphene on silicon carbide, 2016, Vacuum, (128), , 186-197.

<http://dx.doi.org/10.1016/j.vacuum.2016.03.027>

Copyright: Elsevier

<http://www.elsevier.com/>

Postprint available at: Linköping University Electronic Press

<http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-129150>

Invited review

Device applications of epitaxial graphene on silicon carbide

M. Beshkova^{a,*}

mbeshkova@yahoo.com

L. Hultman^b

larhu@ifm.liu.se

R. Yakimova^b

roy@ifm.liu.se

^aInstitute of Electronics, Bulgarian Academy of Sciences, 72 Tzarigradsko Chaussee Blvd, 1784 Sofia, Bulgaria

^bDepartment of Physics, Chemistry, and Biology (IFM), Linköping University, SE-581 83 Linköping, Sweden

*Corresponding author.

Abstract

Graphene has become an extremely hot topic due to its intriguing material properties allowing for ground-breaking fundamental research and applications. It is one of the fastest developing materials during the last several years. This progress is also driven by the diversity of fabrication methods for graphene of different specific properties, size, quantity and cost. Graphene grown on SiC is of particular interest due to the possibility to avoid transferring of free standing graphene to a desired substrate while having a large area SiC (semi-insulating or conducting) substrate ready for device processing. Here, we present a review of the major current explorations of graphene on SiC in electronic devices, such as field effect transistors (FET), radio frequency (RF) transistors, integrated circuits (IC), and sensors. The successful role of graphene in the metrology sector is also addressed. Typical examples of graphene on SiC implementations are illustrated and the drawbacks and promises are critically analyzed.

Keywords: Graphene FET; RF-transistors; IC; Graphene sensors; Detectors; Quantum Hall resistance

1 Introduction

Graphene is a sp² bonded sheet of carbon atoms with honeycomb symmetry that shows non-dispersive transport characteristics. In graphene, electrons move as relativistic Dirac particles with a velocity ~10× higher than in a conventional semiconductor. Carrier mobilities more than 100 000 cm²/V·s [1,2] and saturation velocities of about 5 × 10⁷ cm⁻²s⁻¹ have been reported [3]. These properties in addition to a high current density up to 10⁹ A/cm² and high thermal conductivity up to 5000 W m⁻¹ K⁻¹ [4] make it extremely appealing for applications in electronics. The two-dimensional nature of graphene enables tight control of the carrier density using the field effect [5], and permits the use of conventional semiconductor processing techniques.

It is worth noting that most of these extraordinary properties are related to pristine graphene [6] under slightly idealized conditions such as graphene exfoliated from highly oriented pyrolytic graphite (HOPG), suspending the sheets between metal leads, or using an ultra flat and inert substrate as BN. In research and technology, graphene is used in more complex structures, and at conditions that are determined by the targeted applications. For instance, electrical transport is subject to a variety of scattering events [7–12]. The type of scattering mechanism that dominates in a specific sample could be derived from the magnitude of the carrier mobility (μ), and its dependence on temperature (T) and carrier density (n) [13]. Therefore, mobilities greater than 100 000 cm²/V·s are known to indicate scattering that is dominated by acoustic phonons, where μ_{AC} ~ 1/n [1,2,9]. This is typical for graphene when the substrate is removed and it is heated in order for the adsorbates to volatilize. Long-range Coulomb scattering results in mobilities of the order of 1000–10 000 cm²/V·s that are independent of carrier density, n [8,10,11]. It is related with charge impurities on graphene or more likely at the supporting insulator substrate. Neutral defects become significant in either highly defective samples or at high carrier densities and mobility dominated by short-range scatter, μ_{SR} ~ 1/n [7,11,14,15].

In most of the electronic applications graphene is supported by a dielectric substrate (typically SiO₂ or high-k dielectrics) or by semi-insulating SiC. In this cases the values of the electron mean free path l_{gr} and mobility observed in

supported graphene are usually significantly lower than in a suspended one. Sonde et al. [16] studied the local ℓ_{gr} in graphene deposited on 4H—SiC (DG-SiC) i.e. (graphene exfoliated from highly oriented pyrolytic graphite (HOPG) and deposited on 4H—SiC(0001)), graphene epitaxially grown on 4H—SiC(0001) (EG-SiC) and graphene deposited on SiO₂ (DG-SiO₂), by scanning capacitance spectroscopy. The electron mean free path in DG-SiC was more than four times longer than in DG-SiO₂. This difference can be related to the difference in the permittivity of SiC ($\epsilon_{SiC} = 9.7$) and SiO₂ ($\epsilon_{SiO_2} = 3.9$), and respectively to the lower coupling of the 2DEG (two-dimensional electron-gas) with SPP (surface polar phonons) in SiC than in SiO₂. On the other hand ℓ_{gr} in EG-SiC is on the average 37% of the ℓ_{gr} in DG-SiC and exhibits large variations from point to point, due to presence of a laterally inhomogeneous positively charged layer at the EG/SiC interface.

Giannazzo et al. [17] used a method based on scanning capacitance microscopy/spectroscopy to obtain 2D maps of the electron free path (ℓ) in graphene obtained by mechanical exfoliation of highly oriented pyrolytic graphite (HOPG) and deposited on substrates with different dielectric permittivity, that is, SiO₂ ($k_{SiO_2} = 3.9$), 4H—SiC(0001) ($k_{SiC} = 9.7$) and the very-high-k perovskite strontium titanate, SrTiO₃(001), referred to briefly as STO ($k_{STO} = 330$). Such maps are a powerful instrument to understand the scattering mechanisms such as charge impurities (CI) and resonant scattering (RS) limiting the transport properties in graphene at room temperature. CI can be adsorbed on graphene, or located at the graphene/substrate interface while, according to the density functional theory calculation, RS in graphene occurs naturally for vacancies, and adsorbates like H, OH and CH₃, CH₂OH [18]. It was shown that CI are the main source of the lateral inhomogeneity of ℓ in graphene on low-k substrates, while the role of RS as a limiting factor for ℓ was more pronounced in graphene on high-k STO.

For high performance applications mobility maximization and uniformity are required at the wafer scale, therefore techniques producing graphene with unique azimuthal orientations over a whole wafer are needed. In the following we discuss graphene materials grown on SiC which meets the above requirements.

The graphitization of hexagonal SiC crystals during annealing at high temperature in vacuum was reported by Badami DV as early as 1962 [19]. Under such annealing conditions the top layers of SiC crystals undergo thermal decomposition. Since Si has the highest partial vapor pressure, Si leaves the surface while C nominally remains on the surface, rearranges and re-bonds to form epitaxial graphene layers possessing in-plane sp² bonding [20–22].

Graphene formation occurs in a top-down manner starting by decomposition of the SiC substrate surface and proceeding into the SiC bulk [23,24]. Decomposition of about three Si—C bilayers (~0.75 nm) is required in order to arrange one graphene layer (~0.34 nm). On the Si face of SiC, initially a C-rich ($\sqrt{3} \times \sqrt{3}$) R30° surface reconstruction occurs, which is known as a buffer layer or zero graphene layer [25]. In such layers the C atoms are arranged in a similar honeycomb structure to graphene, but there is 30% covalent bonding to underlying Si atoms [17]. Thus the buffer layer provides a template for subsequent epitaxial growth. It has been debated whether growth of graphene on SiC is really epitaxial under conditions of a large lattice mismatch between SiC (3.073 Å) and graphene (2.46 Å) as the carbon self-rearranges on the SiC substrate surface rather than being deposited on the SiC surface, as would arise in a classical epitaxial growth [26]. However, it has to be noticed that growth of graphene on SiC by Si sublimation does not occur on a pristine SiC surface, but is mediated by the C-rich reconstructed surface which, due to its structural compatibility with grapheme, appears to be a perfect template for graphene formation in an ordered manner, i.e. epitaxially.

In terms of electrical properties, the buffer layer is not equivalent to graphene. This layer is not conducting and does not bear the electronic properties of graphene because of the sp³ bonding to the SiC substrate. The buffer layer is responsible for the n-type doping of pristine graphene on SiC (0001) due to the presence of unsaturated Si bonds.

In the course of graphene growth a new buffer layer forms below the first one that is simultaneously converted to graphene. A second graphene layer can grow in the same manner. It is more difficult to grow multilayer graphene on SiC [27] due to the decreased Si desorption rate from the buried SiC decomposition front. Si removal in this case occurs via diffusion through defects in graphene (mainly terrace edges) and/or the sample edge. More graphene layers form when pronounced defects, like polishing scratches and micro-pipes, are present on the substrate surface.

It has been shown that the graphene on Si-face SiC grown at high temperature, 2000 °C, possesses superior properties such as structural integrity and uniformity of graphene over hundreds of micrometers, as well as reproducible mobility and carrier concentrations across a half-centimeter wafer, which allowed precise measurements of quantum Hall resistance [28].

On the other hand, on the C face of SiC the first graphitic layer grows on top of the SiC substrate without causing a strong rearrangement of the surface structure. There are still debates about the structure of the interface layer, i.e. whether graphene growth on the C face is preceded by ordered surface reconstructions [29] or a disordered/amorphous interface layer [30].

Low bias STM (scanning tunneling microscopy) images revealed a graphitic structure, indicating that the interaction between graphene and the SiC surface is weaker on the C face than on the Si face of the SiC substrate [29].

Coby et al. [30] report formation of an amorphous layer at the interface of graphene films grown via thermal decomposition of C-face 4H—SiC at 1600 °C. Electron energy loss spectroscopy (EELS) demonstrates that the amorphous layer is carbon-rich. Few-layer graphene films grown under similar conditions on Si-face substrate were not observed to contain any such amorphous layer [31].

Nicorta et al. [32] show that for high growth temperatures like 1900 °C the graphene/SiC (000 $\bar{1}$) interface is dominated by a thin amorphous film which strongly suppresses the epitaxy of graphene on the SiC substrate, since its thickness ~1.1–1.4 nm is bigger than the range of chemical bonds between atoms of the first graphene layer and the last SiC bilayer. This film maintains an almost fixed thickness regardless of the number of the overlying graphene layers. High-resolution EELS shows the presence of C, Si and O. Structurally, the amorphous layer is inhomogeneous, as its Si concentration gradually decreases while moving from its substrate-looking side toward graphene. The presence of oxygen is due

to the stronger reactivity of the amorphous interface which allows its incorporation during and after the sublimation process.

Bouhafas et al. [33] showed an increase in the thickness of the amorphous layer between graphene and 4H—SiC (0001) with increasing growth temperature of 1800 °C, 1900 °C and 2000 °C using independently SE (spectroscopic ellipsometry) and HRTEM (high resolution transmission electron microscopy) analysis.

Ostler et al. [34] demonstrated with the aid of XPS (x-ray photoelectron spectroscopy), ARPES (angle-resolved photoelectron spectroscopy), LEEM (low-energy electron microscopy), and DFT (density functional theory) that, if the graphitization process starts from the nonpolar (1120) and (1100) planes of hexagonal SiC, no buffer layer is formed. On SiC (1100) the graphene layer thickness distribution is difficult to control while on SiC (1120) the graphene coverage is more uniform with larger areas of monolayer graphene.

Reasonable understanding of graphene growth modes has been reached for existing SiC polytypes [35]. A study by Robinson et al. [36] found that the graphene uniformity and carrier concentration of graphene grown on SiC substrates are correlated with the SiC off-cut angles and the crystallographic orientation of the miss-cut. Nicotra et al. [37] studied the properties of epitaxial graphene over the steps of 4H—SiC(0001) substrates with an 8° off-axis angle in the [1120] direction. The combined analysis of scanning transmission electron microscopy (STEM), electron energy loss spectroscopy (EELS) and conductive atomic force microscopy (CAFM) offer evidence that the typical buffer layer on the planar (0001) face of SiC detaches from the substrate on the (112n) facets of the steps, and becomes quasi-freestanding graphene. This fact may explain the observed local rise of the graphene sheet resistance due to a lower substrate-induced doping and the appearance of an additional graphene layer at the step facets. A very localized enhancement in the resistance was detected at the junction between monolayer (1L) and bilayer (2L) graphene regions using CAFM. First-principles transport calculation clarified the purely quantum mechanical origin of this phenomenon, i.e., weak wave-function coupling between the 1L π/π^* bands with the respective first bands of the 2L region gives rise to a strong suppression of the conductance for energies within ± 0.48 eV from the Dirac point [38].

Growth of graphene on off-xis SiC (4° or 8° off cut) with low doped epilayers is of interest from a point of view of transistor design and integration of the graphene devices with such on SiC. However, graphene growth on off-cut substrates is a challenging task when 1 ML graphene is targeted. Commonly multilayer graphene is formed which is accompanied by new morphological features. Tapping mode ("Tapping mode" is not necessary to be Bold,) atomic force microscopy (t-AFM) showed the formation of wrinkles with approximate 1–2 nm height and 10–20 nm width in the few layers of graphene (FLG) grown on 4H—SiC(0001) 8° off-axis. The wrinkles are preferentially oriented in the direction perpendicular to the step edges of the SiC terraces as a result of the release of the compressive strain accumulated in FLG during the sample cooling due to a thermal expansion coefficient mismatch between graphene and SiC [39]. Further Eriksson et al. [40] elucidated the influence of surface morphology on the electronic properties of epitaxial graphene, and in particular how it affects the thickness uniformity and the unintentional doping from the substrate. He found that the monolayer coverage depends on the terrace width of the as-grown EG/SiC. A more homogeneous coverage is favoured by wider terraces in the range of 300 to approx. 1200 nm. It was also observed that increasing the terrace width from 300 nm to 1200 nm resulted in an estimated reduction of n-type carriers by $8 \times 10^{12} \text{ cm}^{-2}$.

In addition to thermal decomposition of SiC, graphene grown by CVD (Chemical Vapor Deposition) on SiC substrates is under development [41,42]. The CVD of graphene using a propane gas as the carbon precursor relies critically on the creation of dynamic flow conditions by Ar in the reactor that simultaneously stop the Si sublimation and enable the mass transport of the propane to the SiC substrate. The value of the Reynolds number was tuned, experimentally to enable the formation of an Ar boundary layer that is thick enough to stop Si evaporation but thin enough to allow the diffusion of propane to the SiC surface [41]. Further the same group [43] study morphological and electronic properties of nitrogen-doped epitaxial graphene grown by CVD on 4H—SiC(0001) since nitrogen doped graphene is important in biological applications, as the nitrogen doping may enhance biocompatibility of the carbon-based material [44,45]. Recently, CVD grown graphene on SiC was reported to possess properties required for quantum metrology. This original hybrid growth method is employing the advantages of both the growth on a single crystal substrate like SiC and CVD as a tunable method [46].

A number of reviews describing physical properties of graphene [46,47], graphene synthesis and device applications [48] have been published. Since epitaxially grown graphene on SiC provides potential for the large-scale integration of graphene electronics in this work we present a coherent picture of the achievements of graphene devices on SiC, critically pointing out the advances and the drawbacks.

1.1 Graphene FET transistors for post Si CMOS applications

Graphene is just one or a few atoms thick and exhibits high carrier mobility; hence it is natural to use it in field-effect transistor designs as channel material. In a graphene field-effect transistor (GFET) the transport of the injected carriers in the graphene channel can be controlled by a gate induced-electric field. If a negative bias is applied to the gate it will raise the electron energy, while a positive bias lowers it. Graphene is ambipolar, so that when E_F is below the neutrality point E_{NP} (also referred to as the Dirac point), transport involves holes, while for $E_F > E_{NP}$ electrons are transported. When the Fermi energy is changed by the gate, the density-of-states (DOS) and correspondingly the carrier density ($E_F \sim \sqrt{n}$) will change. This is type of "switching" is characteristic of graphene field effect transistors because graphene is a zero band-gap semiconductor. Hence, unlike transistors processed on conventional semiconductors with an energy band-gap, a GFET does not turn off completely, even though $DOS = 0$ at the neutrality point. There still remains some conductivity of the order of $G_{min} = 4e^2/\pi h$ [49]. This is a serious issue that inhibits graphene application in digital electronics [48]. Typical current on/off (I_{on}/I_{off}) ratios that can be achieved by gating of a graphene transistors are of the order of 10 in a conventional design. This number depends on the quality of graphene and the gating efficiency. Digital transistors utilized in logic applications, on the other hand, require on/off ratios higher than about 10^4 , according to ITRS (International

Technology Roadmap for Semiconductors) [50]. There is much research effort aimed at opening a band-gap in graphene based on i) lateral confinement in graphene ribbons [51,52] and ii) combination of single and bilayer graphene regions [53–55]. Unfortunately, these all present different problems.

Graphene nanoribbons [51,52] exhibit a very interesting device behavior [56], but they have to be extremely narrow (smaller than 3 nm) with very small deviation in the width in order to avoid uncontrollable changes in the band-gap. It has been shown that a band-gap of 100–150 meV can be induced in bilayer graphene by applying a perpendicular electrical field. However this band-gap is not sufficient to obtain high enough on/off ratios [52] for transistor applications.

Zhou et al. [57] experimentally demonstrated by angle-resolved photoemission spectroscopy that a graphene grown on a SiC substrate had a gap of about 0.26 eV, which makes it a promising channel material for FETs. The authors believe that the bandgap is induced by the symmetry breaking in graphene A and B sub-lattices due to interaction with the substrate. Unfortunately, data about on/off ratio have not been provided.

From a manufacturing point of view, it is highly convenient to prepare an entire substrate of graphene on an insulator and then obtain single devices and integrated circuits through patterning [58].

Kedzisi et al. [58] reported MEG (multilayered epitaxial graphene) transistors built on both the C- and Si-faces on SiC. Measured mobilities indicate that the graphene structure non-uniformities are responsible for the mobility variation between chips and faces. Typically the Si-face multilayered graphene show a significantly lower mobility than the C-face multilayered graphene. Mobilities as high as 5000 cm²/V-s were obtained for C-face devices.

Yoh et al. [59] measured device characteristics of graphene FETs grown on Si-face 4H-SiC that show typical ambipolar effect against gate voltage and drain current versus drain voltage characteristics ($I_{ds}-V_{ds}$) curve with on/off ratio over 100 at 1.4 K.

Cheli et al. [60] proposed a model of a nanoscale FET based on epitaxial graphene on SiC for digital applications, with on/off ratio of 50 and a sub-threshold slope of 145 mV/dec that can be obtained with a supply voltage 0.25 V. This represents significant progress toward solid-state integration of graphene electronics, but not yet sufficient for digital applications. Via theoretical modelling it was predicted [61] that the ITRS (International Technology Roadmap for Semiconductors) requirements can be met using graphene-on-SiC Tunnel Field Effect Transistors (TFET) with on/off ratios exceeding 10⁴ even with a low supply voltage of 0.15 V for devices with a gate length down to 30 nm (Fig. 1). Here, an energy band-gap of 0.26 eV [57] was assumed.

Fig. 1 I_{ON} and I_{OFF} table for TFET devices with supply voltage $V_{DD} = 0.1, 0.15, 0.2$ and 0.25 V, and channel length L_C between 10 and 50 nm. It is considered here the thickness of silicon oxide layer $t_{ox} = 1$ nm and doping concentration $\alpha = 3 \times 10^{16} \text{m}^{-2}$. A dashed line marks the field where $I_{ON}/I_{OFF} \geq 10^4$ [61].

Another approach in obtaining a high on/off current ratio of 2.7×10^3 is to use semiconducting source/drain regions as proposed in Refs. [62–64]. This device is referred to as a semiconductor/source/drain GFET (SGFET). These two types of FETs were both fabricated using the same processes.

First ion -implantation was carried out. The doped source and drain regions (the n-SiC and n⁺-SiC regions in Fig. 2b) were formed by implanting P⁺ ions at room temperature (RT) followed by implanting B⁺ ions at RT. B was introduced into the SiC substrates under the graphene channel region to avoid parasitic metal-oxide-semiconductor FET (MOSFET) operation. After the ion implantation process, activation annealing was carried out in an Ar atmosphere. The effective depths of both the P⁺ and B⁺ were 0.2 μm .

Fig. 2 (a) and (b) Schematic illustrations of the GFET and SGFET structures, respectively [64].

After formation of the doped regions, graphene layers were formed on the SiC (0001) surface in a following manner; 0–2 monolayers (MLs) of graphene were grown on a monoatomic interfacial layer called zero-layer (ZL) and earlier explained as a buffer layer, by vacuum annealing. The 0–2 graphene MLs on the ZL were converted into 1–3 MLs of graphene without a ZL by annealing in hydrogen in order to achieve well-controlled interface with a low number of traps and no Fermi-level pinning. The graphene channels were patterned by in an O₂ plasma. The gate dielectric (Al₂O₃) was deposited by metal-organic chemical vapor deposition. An aluminum gate electrode was deposited by thermal evaporation and patterned using a wet etching process. Contact holes for the source and drain regions were formed by hydrofluoric (HF) acid wet etching. Then, titanium source and drain electrodes were deposited by electron beam evaporation and patterned with a lift-off process. The channel length (L) and width (W) of the fabricated GFETs were 40 μm and 20 μm, respectively and they were both 20 μm of the SGFETs. The shorter channel length of the SGFETs contributed to it having a higher drain current than the GFET. The value of the on/off ratio for the SGFETs could be determined by the modulation range of the Schottky barrier height. Fig. 2 (a) shows a conventional GFET with metal source/drain electrodes and 2(b) SGFET with n-SiC source/drain regions with the ~~Schottky~~ Schottky barrier at the graphene/n-SiC contact.

S. Hertel [65] proposed a metal semiconductor field-effect transistor structure in which n-doped SiC plays the role of semiconducting channel material, as-grown monolayer graphene (MLG) is used as source and drain electrodes and quasi-free-standing bilayer graphene (QFBLG) as the Schottky gate. The latter is obtained by local hydrogen intercalation. The transistor has on/off ratio which is within 3–4 orders of magnitude depending on the operation mode. This is a non-conventional concept because it operates only on graphene, SiC and their interfaces. The device performance is not essentially limited and may be custom-made according to specific requirements. In particular, the contact resistances can be improved by four orders of magnitude by contact implantation. Different intercalation conditions, variation of off-angle of the substrate, design optimization, and so on are expected to lead to uniform and therefore higher effective Schottky barriers. This will allow for higher currents, higher operation speed and higher operation temperatures that can be suitable for more stringent operation conditions.

Waldmann et al. [66] presented a scheme (Fig. 3) for the fabrication of bottom-gated epitaxial graphene devices, which is based on nitrogen implantation into a SiC wafer and subsequent graphene growth. The device can work in a broad temperature range (6–300 K). Ultimately two gating regimes can be employed, which opens a wide engineering area for tailored devices by adjusting the doping of the gate structure. Such a bottom-gate structure is suitable for both small size devices and on the wafer scale. The characteristics can be modified over a wide range by appropriate selection of the doping concentrations. Since the bottom gate allows the graphene surface to be exposed, various surface treatments are possible on a working device. Therefore, the device concept opens new pathways for stimulating applications in science and technology.

Fig. 3 Set-up of the bottom gate with source (S), drain (D) and gate (G) electrodes on graphene; conductive gate layer and implanted connections [66].

The continuous device scaling and performance improvements required by the ITRS are facing a grand challenge as conventional Si CMOS (complementary metal-oxide-semiconductor) scaling comes to its fundamental physical limits. New solutions are expected from graphene researchers.

Ye et al. [67] reported an epitaxial graphene MOSFET (metal-oxide-semiconductor field-effect transistors) as a novel channel material with extracted electron effective mobility as high as 5400 cm²/V·s. The graphene films were grown on the carbon face of semi-insulating 4H — SiC by hot-wall CVD. This carrier mobility is already ten times better than silicon technology, which has decades of optimization.

Transistor concepts based on graphene nano-ribbons (GNR) may open a new pathway towards digital logic devices. However, the creation of controlled band-gaps by quantum confinement of carriers in GNRs remains a significant challenge for circuit implementation by conventional lithographic processes. The methods that allow fabrication of GNRs down to sub-5 nm width are not yet site-controlled or reproducible.

Recently, a promising solution has been proposed by Hwang et al. [68] who report the fabrication of top-gated ~10 nm wide GNRFETs by lithography on large area epitaxial graphene (EG) on SiC substrates. They observe for the first time, the opening of

a substantial energy gap inversely proportional to the GNRFET width of EG-GNRs. By relating the measured transport with theoretical modelling, they find that the transport properties of narrow epi-GNRs are similar to well-behaved narrow-band-gap semiconductors, contrary to carrier localization effects reported extensively in wider GNRs fabricated on exfoliated graphene. For a 10 nm wide GNR, the energy gap is 0.14 eV. GNRs were prepared on 4 inch SiC wafer which enabled processing of arrays of FETs. The array GNRFETs consisting of parallel arrays of 30 GNRs were fabricated and the I_D versus V_{GS} of the 30-array GNRFET was compared with that of a single GNRFET. An increase of the drain current was observed, which is one of the benefits of array GNRFETs. They also observed a high maximum drain current density of 12 mA/ μm from the total channel width. Such high current drives have never been reported in any semiconductor device. This high current carrying capability was attributed to the high electrical and thermal conductivity of the GNR channels due to the absence of lateral scattering, coupled with the excellent thermal conductivity of the underlying SiC substrate. The high current drives are attractive from many viewpoints: for high-performance transistors with fast switching and possibly for integrated interconnects. The authors expect that with further scaling of the widths of wafer-scale clean GNRFETs, graphene based transistors can show promising potential for practical applications. However the on/off current ratio of $10\times$ at room temperature is still not sufficient, which implies further that increase of the band-gap, by reduction of the ribbon width is required.

1.2 Graphene RF-transistors and amplifiers

As discussed in the previous section, use of graphene as a digital switch is not straightforward due to the absence of an energy band-gap. However, its outstanding carrier mobility, the high transconductance of graphene devices, and the atomic size thinness and robustness of the material are excellent merits suited for high speed analog electronics; precisely radio-frequency (RF) transistors. In analog RF applications, though appropriate, it is not critical to completely switch-off the device [48]. Taking as an example signal amplifiers, which is the major application of RF transistors, the transistor is in the on-state and the RF signal to be amplified is superimposed on the DC gate bias.

One of the most important figures-of-merit for judging the performance of RF devices is the cut-off frequency, f_T . It is defined as the frequency at which the short circuit current gain becomes unity and is normally used to compare the capabilities of different channel materials. In a RF device $f_T = g_m/2\pi C$, where g_m ($g_m = dI/dV_g$) and C are the dc transconductance and capacitance of the device, respectively [5,69]. Optimization of f_T in graphene FETs involves increasing g_m and minimizing the capacitance. Cut-off frequencies are important for determining the intrinsic speed of these devices. For analog applications, another valuable figure-of-merit is the maximum oscillation frequency f_{max} [70]. This value is typically defined as the frequency at which unilateral gain (U) becomes unity [71]; f_{max} is the highest possible operating frequency before a transistor loses its ability to amplify power. Both f_T and f_{max} are important figures of merit of transistor performance. The first one reflects the intrinsic behavior of a transistor channel, whereas the second one also strongly depends on the device layout and can be further enhanced, for example, by optimizing the gate contact leads.

Promising results were published [73] demonstrating RF GFET with $f_T = 100$ GHz processed on wafer-scale graphene on SiC. This 100-GHz cut-off frequency exceeds those of graphene FETs previously reported [72] as well as those of Si MOS FETs of the same gate length (~ 40 GHz at 240 nm). Although current saturation was difficult to achieve and f_{max} was not sufficiently high, this pioneering work has demonstrated the high potential of graphene on SiC for electronic device applications. It should be noted that the graphene used primarily had a modest mobility of ~ 1500 cm² V⁻¹s⁻¹ and the gate length was, by today's industry standards, long (240 nm). This suggests that the material and device optimization could lead to drastic improvements in device performance. In fact, the second generation of SiC-based GFETs showed much higher f_T values, e.g., exceeding 300 GHz, with 40 nm channel length (Fig. 4) [74,75]. Furthermore, better current saturation and thinner gate oxides have resulted in an improved f_{max} of ~ 40 GHz. Wu et al. [75] demonstrated RF devices with optimized design showing voltage and power gains attaining 20 dB. Voltage gain of more than 20 dB at 1 GHz was measured for longer channel devices. This can be explained by the better current saturation behavior with smaller output conductance (g_d) in these devices. This large voltage gain is the highest achieved so far using graphene.

Fig. 4 Performance characteristics of GFET: Plot of current gain (h_{21}) for two 40 nm devices based on epitaxially grown graphene and f_T of 300 and 350 GHz [75].

In Fig. 4 the RF performance of epitaxial graphene grown on SiC is analyzed.

The peak f_T is above 300 GHz for 40 nm devices with the highest value of 350 GHz obtained from the best device. This is also supported by the dc projection of $f_T = g_m/2\pi C_{ox}$ where g_m is the transconductance and C_{ox} is the gate capacitance. The

experimental results are consistent with the value derived from the modelling by Gummel's method [76] shown in the inset [75].

1.3 Wafer-scale graphene integrated circuits (IC)

Stimulating advancement has been achieved in discrete transistors and circuits operating on single graphene devices [77–79]. Lately, the first wafer scale graphene broadband frequency mixer, operating at frequencies up to 10 GHz, was fabricated on graphene on SiC [80]. In this IC circuit all GFETs and inductors were realized on a single wafer. Mixing was achieved by the FET channel resistance modulation which is a different concept from the conventional mixers where nonlinear devices like Schottky barrier diodes are used. The mixer performance was insensitive to temperature changes and this is a clear advantage of graphene usage in such IC applications. The performance of the frequency mixer is displayed in Fig. 5.

Fig. 5 Output spectrum of the graphene made mixer between 0 and 10 GHz using an input RF frequency, $f_{RF} = 3.8$ GHz and a local oscillator frequency, $f_{LO} = 4$ GHz. Each x and y division corresponds to 1 GHz and 10 dBm, respectively. The input RF power was adjusted to 0 dBm with respect to the RF input. The frequency mixing is observed as two peaks (f_F) at 200 MHz and 7.8 GHz [80].

Frequency mixing based on the ambipolar behavior of graphene has also been demonstrated [77]. These results suggest that complex graphene devices with functional performance can be made on epitaxial graphene.

IC voltage amplifiers based on graphene of wafer scale have been fabricated [75,77] but only moderate power gains (3 dB) have been demonstrated up to now (Fig. 6). Achieving better current saturation and thus increasing the gain are currently the focus of much effort.

Fig. 6 Characteristics of wafer scale integrated circuit of graphene amplifier. The measured voltage gain (V_g) versus drain current at 5 MHz for a 1.5 μm device with a maximum gain of 3 dB [75].

Moon et al. [81] suggested a completely passive resistive FET mixer in short gate length graphene FETs. It was shown that with no drain bias, no DC power dissipation is consumed. The conversion loss of 14 to 17 dB is demonstrated at 2 to 10 GHz and 18 dB at 20 GHz.

Madan et al. [82] reported graphene RF mixers in the ambipolar geometry, using quasi-free-standing epitaxial graphene on SiC. Ambipolar mixing was achieved via gate mixing of the LO (local oscillator) and RF input signals. They measured very high conversion gain by using optimized growth and synthesis techniques, metal contact development, and dielectrics integration. Hydrogen intercalation was employed to separate the graphene from the SiC substrate and improve the transport properties, e.g., carrier mobility was as high as 3000 $\text{cm}^2/\text{V}\cdot\text{s}$ at 10^{13} carriers per cm^2 . Low contact resistances at the metal-graphene interface are achieved by oxygen plasma pre-treatment, whereas dielectric seeding is attained using a direct deposited layer of HfO_2 before ALD film growth. In order to achieve record high conversion gain of -14 and -16 dB at LO power 0 dBm at 4.2 and 10 GHz, respectively a graphene RF transistor is designed with gate length 750 nm, width 20 μm , and equivalent oxide thickness ~ 2.5 nm. This result is 100 $\times$ better than previously reported ambipolar mixing.

S. Hertel et al. [83] reported a new concept of monolithic circuits for digital operation based on low cost n-type SiC substrates on which p-type epilayers are grown to form a p-n junction. Graphene grown on top is locally hydrogen intercalated under the gate. The authors significantly improved the transistor parameters and go beyond the single transistors by connecting resistors and transistors to simple circuits. In particular, they show inverter and NAND gate operation. Although the processing comprises rather too many key steps, the proposed scheme is suited to form complex circuits and a full digital logic while the concept adds full digital functionality to graphene high-frequency electronics on the wafer scale.

1.4 Graphene detectors

Small (micron and submicron sized) semiconductor Hall effect devices [84] have been successfully used for magnetic field sensing in industrial applications [85–87]. Graphene is an ideal material for Hall elements which may connect the remarkable properties of graphene, i.e. extremely high carrier mobility and atomically thin active layer, to produce magnetic sensors with high sensitivity, excellent linearity and remarkable thermal stability [88]. Panchal et al. [89] fabricated graphene Hall sensors with the width ranging from 0.5 to 20 μm . The epitaxial graphene was grown by sublimation of Si and subsequent graphene formation on the Si-terminated face of a nominally on-axis 4H—SiC substrate at 2000 °C and 1 bar argon gas pressure [90]. The minimum detectable field of a typical 10- μm graphene sensor is $\approx 2.5 \mu\text{T}/\text{Hz}$, making them comparable with state of the art InSb semiconductor devices of the same size and carrier concentration [91–93] and superior to device made of CVD graphene, capable to detect magnetic fields $\approx 43 \mu\text{T}/\text{Hz}$ [94].

The applicability of quasi-free standing (QFS) graphene on SiC for magnetic field detection has been recently addressed by [Ref. \[95\]](#), who focused on material issues. Initially graphene was deposited on the Si-face of SiC by CVD while QFS bilayer graphene was made by hydrogen atom intercalation of monolayer graphene. This graphene exhibits high carrier mobility reaching 5000 cm^2/V , and electrical stability throughout the device processing cycle. The problem of the step-edge-induced offset voltage anisotropy in Hall effect sensors is discussed. It comes from the step-terrace geometry of the SiC substrates which typically results in graphene thickness non uniformity originating from the step edges. The impact on the quantum Hall effect has been elucidated in [Ref. \[96\]](#). Step edge induced resistance anisotropy was revealed in CVD graphene on SiC [97]. Based on that it was concluded in [Ref. \[95\]](#) that in Hall effect sensors the step-edge-induced offset voltage anisotropy, which is a threat to the device operation, needs to be minimized by consciously orienting the Hall element, so that the constant electric current flows either in the direction perpendicular or parallel to the pattern of silicon carbide terraces and step edges.

THz radiation is very promising for many application fields, especially because there is a “terahertz gap” that reflects the lack of both THz sources and detectors which are easily and economical to operate. One possibility for the realization of a THz detector is by exploiting the Landau quantization in quantum Hall detectors based on graphene.

Direct RF to mm-wave detection is used for power detectors in mobile communications, cellular handsets, and test equipment for power monitoring and control. For RF to mm-wave power detectors, the linear-in-decibel dynamic range is important. In the silicon CMOS transistor-based detectors the linearity of the dynamic range is poor. Moon et al. [81] reported graphene FETs detectors, in which the DC output voltage is very linear concerning the input RF power level, representing a >40 dB linear-in decibel region with square-low detection.

Sensitive room-temperature terahertz detectors have been recently featured in Nature nanotechnology [98]. It is suggested that significant improvements of room-temperature graphene terahertz detectors are possible using local gates or locally doped regions to define p–n junctions.

Using SiC as a substrate for graphene, offers the possibility of vertical device design based on semiconductor heterojunctions. Anderson et al. [99] made a UV detector based on an epitaxial graphene/SiC heterojunction. The application of graphene is to minimize absorption losses, resulting in high-efficiency sensing while maintaining the low dark current associated with a p–n junction.

1.5 Graphene based sensors

The energy band structure of graphene is unique with its linear and vanishing density of states about the Dirac point which makes it extremely sensitive to chemical gating because the Fermi level changes largely with small changes in carrier concentration. The latter can be caused by adsorbed molecules donating or withdrawing electrons. It has been shown that since single layer graphene sensors have every atom exposed at the surface, they have the potential of high sensitivity, down to single molecule detection at low power and room temperature [100]. In the same article it is stated that sensors made from graphene are capable of detecting individual events when a gas molecule attaches to or detaches from a graphene surface. The adsorbed molecules change the local carrier concentration in graphene, which leads to step-like changes in resistance. The achieved sensitivity is also due to the fact that graphene is an exceptionally low-noise material electronically [101]. Sensors utilizing epitaxial graphene on SiC have the potential to avoid graphene transfer and its subsequent placement on a desired substrate which is a mandatory procedure in the case of any other type of graphene [100]. Hence, simpler and more reproducible devices can be produced. Epitaxially grown graphene on SiC has, as a sensor material, major advantages over graphene produced by exfoliation from HOPG (highly-ordered pyrolytic graphite) or by reduction of graphene oxide, such as coverage, homogeneity and control over the number of graphene layers, and consequently, electronic properties.

In a much cited work, Pearce et al. [102] fabricated simple resistive gas sensors on epitaxial single layer and multilayer graphene on SiC for ultra-sensitive NO_2 detection. The response to 2.5 ppm NO_2 of the multi-layer sensor after 1 h exposure time at 25 °C was $\sim 0.01 \Omega$. In contrast, the single layer graphene on SiC sensor provided a response of $\sim 550 \Omega$ after 1 h exposure time at 25 °C ([Fig. 7](#)).

Fig. 7 Response of single layer graphene sensor towards NO₂ in a carrier gas of N₂ with 20% O₂ at 25 °C [102].

The extreme sensitivity of the single layer graphene device is assumed to be due to the low concentration of charge carriers. The lower sensitivity of the multi-layer device is proposed [102] to be related to some additional conduction through graphene layers that are not exposed to the gas. The lower sensitivity may be also due to a higher number of charge carriers in the top graphene layers which are screened from the electron donation of the SiC substrate and are exposed to hole doping by oxygen from the environment. The response of the multi layer graphene device is comparable to nanocrystalline graphitic materials grown on SiC [103]. The importance of using one monolayer graphene to increase the sensitivity of gas sensors is further elucidated [104,105].

Fig. 8 demonstrates that the response of sensors made on 1 ML graphene is fully reproducible [106].

Fig. 8 Response to NO₂ of three sensors processed on ML graphene on SiC. (courtesy J. Eriksson) [106].

Large area graphene (mm scale) commonly exhibits bilayer (2LG) patches of μm size. Although small, they affect the graphene carrier concentration and mobility locally and may contribute to an inferior performance when found in a device area. This is due to the fact that the energy-k dispersion in a bilayer graphene deviates from the linear one tending to parabolic. Bilayer regions were identified by scanning Kelvin probe microscopy (SKPM) [40,104] optical microscopy [107] and optical reflectance mapping [108]. The effect of bilayer areas on the electronic response to environmental gating of a monolayer graphene Hall bar device is investigated [105]. Environmental gating involves the donation and withdrawal of electrons by the controlled adsorption of gas molecules which shift the Fermi level of graphene. In this case there is no need of a dielectric inducing large effective fields. The effective gate voltage is determined by the concentration of adsorbates and the amount of charge transferred by each adsorbed species. The effective charge or equivalent gate voltage on the graphene device can be tuned from electron-doped to hole-doped by the adsorption of electron withdrawing gases which neutralize the electron donation from the buffer layer. Controlled environment SKPM of devices allows unparalleled access to the device surface enabling the changing work function of the device to be mapped as it is tuned through the charge neutrality point. While gated transport measurements can be used to show the overall response of the device they do not show nano-scale effects of inhomogeneity on the device response. A combination of controlled environment transport and SKPM measurements is thus useful for understanding the effect of 2LG inclusions and changing contact resistance for sensing applications and enables a nanoscale understanding of gating effects for all graphene devices.

In a very recent paper A. Di Bartolomeo [109] has reviewed the state-of-the art of the research on graphene/semiconductor Schottky junctions and their possible applications. It is emphasized that such structures have a great potential for gas sensor devices. In the case of epitaxial graphene on SiC it is pointed out that the Schottky barrier is lowered by the n-type doping from the substrate due to the different work functions of SiC and graphene. The charge transfer from SiC to graphene was studied in Ref. [94-110] where the saturation density of n-type doping of single layer graphene was estimated around 10^{13} cm^{-2} (corresponding to $E_F \sim 0.4 \text{ eV}$) for a 0.3 nm SiC surface-to-graphene spacing and a bulk donor density 10^{19} cm^{-3} in the SiC buffer layer. Since the number of studies of Schottky diodes made on epitaxial graphene on SiC is limited [110-111] it is too early to conclude on the prospective of such devices. Moreover, it has been unambiguously demonstrated that a workable Schottky contact can be achieved after hydrogen intercalation [65].

For the graphene solution-gated field effect transistors (SGFETs), the reported high carrier mobilities for electrons and holes suggest devices with large transconductances and, thus, high sensitivities. Besides the detection of electrolyte properties, such as pH or ionic strength [112], graphene SGFETs are also appropriate for the studies of complex systems, e.g. electrical activity of living cells [113].

Hess et al. [114] show performance of graphene SGFETs in terms of gate sensitivity and compare to other SGFETs technologies. He found the graphene transistors to be clearly superior, confirming the potential of graphene SGFETs for sensing applications in electrolytic environments.

Graphene SGFETs were prepared from epitaxial graphene on the Si-face of SiC by thermal decomposition at 1600 °C under argon atmosphere [115]. Table 1 compares the graphene transistors to SGFETs based on silicon, diamond, and AlGaIn/GaN heterostructures [114,116–118].

Table 1 Comparison of the materials properties and the measured maximum transconductance for silicon, diamond, AlGaIn/GaN, and graphene SGFETs. The values for mobility and capacitance correspond to the gate voltage, where g_m is maximum, μ is carrier mobility, C_{int} is interfacial capacitance, and g_m/U_{DS} is normalized transconductance [114,116–118].

Material	μ (cm ² /V·s)	C_{int} (μF/cm ²)	g_m/U_{DS} (mS/V)
Silicon	450	0.35	0.20
Diamond	120	2	0.29
AlGaIn/GaN	1240	0.32	0.51
SiC-graphene	400	2	1.14

The transconductive sensitivity of the SiC-graphene is found to exceed 1 mS/V, which is 5 times higher than for silicon and can be explained by the combined effect of high interfacial capacitance and the large carrier mobilities in graphene.

Electrochemical immunosensors characteristics are superior to other type of immunosensors. These include high sensitivity, fast response, simplicity, and relatively low cost [119,120].

Teixera et al. [121] report novel chemically-modified epitaxial graphene diagnostic sensor for ultrasensitive detection of the biomarker hCG (human chorionic gonadotropin). This is key diagnostic marker of pregnancy and cancerous tumors found in the prostate, ovaries and bladder. Multi-layer epitaxial graphene (MEG), grown on silicon carbide substrates, was patterned by means of electron beam lithography. The MEG channels were amine terminated using 3-Aminopropyl-triethoxysilane (APTES) for the subsequent attachment of anti-hCG antibody to the channel. Detection of binding of hCG with its graphene-bound antibody was monitored by measuring reduction of the channel current of the graphene biosensor. These graphene biosensors are capable of detecting hCG concentrations as low as 0.62 ng/mL (Fig. 9), 30 times more sensitive than an ELISA test (enzyme-linked immunosorbent assay) performed under the same conditions.

Fig. 9 hCG concentration as a function of the resistance across a 100 μm × 4 mm graphene channel [121].

1.6 Graphene application in metrology

The Quantum Hall effect (QHE) [122], which arises in two-dimensional electron gas (2DEG) systems, allows the international standard for resistance to be defined in terms of the electron charge and Planck's constant, because quantum resistance can be defined by these universal constants. Despite several decades of research on the quantum Hall effect, the level of precision necessary for metrology, a few parts per billion, has been achieved only in a very small number of 2DEG structures, such as Si FET and

III–Vs heterostructures [123]. Among the unconventional transport properties of electrons in graphene, anomalous “half-integer” Quantum Hall Effect has been shown to be promising for development of quantum Hall resistance standard with superior characteristics [28,124,125]. Unusual QHE in graphene has been observed even at room temperature [126]. Graphene, in principle, is an ideal material for applications as a quantum resistance standard, because of a very large spacing of the Landau levels compared to conventional 2DEGs [127]. The QHE resistance standard is supposed to be accurate (no corrections to the fractions of $R_K = h/e^2$), universal (material independent) and robust (same resistance over a range of magnetic fields, temperatures, currents). Graphene on SiC has an additional advantage for quantum resistance metrology that the breakdown current density, i.e. the maximum current that graphene can sustain before quantum Hall effect vanishes, can be at least an order of magnitude higher than the best values achieved in semiconductors [128].

Indeed, in a recent direct comparison of quantum Hall resistance (QHR) between epitaxial graphene and GaAs [124,129], the present system of choice for QHR, the relative uncertainty of 10^{-10} was limited by the lower breakdown current in the GaAs device, suggesting that a graphene-based resistance standard can allow for an even higher precision. Together with possibilities to measure at relatively low field [130] graphene on SiC represents a very promising candidate platform for novel quantum Hall resistance standards with higher performance, higher than the current performance of the existing standards.

Researchers from the National Physics Laboratory (NPL), UK teamed with researchers from Sweden have first demonstrated the potential of epitaxial graphene on SiC for novel quantum resistance standard [28]. Typical layout of the device, which is a Hall bar with eight contacts, is illustrated in Fig. 10 [125]. Hall bars of different size have been used, from $160\text{ }\mu\text{m} \times 35\text{ }\mu\text{m}$ down to $11.6\text{ }\mu\text{m} \times 2\text{ }\mu\text{m}$, but the advantage of the larger size is that it can sustain a much higher current before QHE breaks down.

Fig. 10 Optical microscopy image of the device geometry used in the precise quantum Hall measurements [125].

Monolayer graphene on semi-insulating (0001) terminated 4H—SiC substrates, which showed an excellent suitability for QHE studies and application, was produced by high temperature decomposition/sublimation of SiC [131,132]. The process and the particular substrate support an epitaxial formation of graphene which is a prerequisite of high structure quality material. Typical characteristics are: stepped surface and n-type conductivity with electron concentration in the range of $(5\text{--}8) \times 10^{11}\text{ cm}^{-2}$, and mobility about $2400\text{ cm}^2/\text{V}$ at room temperature. Steps are due to the substrate structure and do not affect the continuity of the grown graphene.

Judging from the robustness of the quantization and wide operational parameter space, epitaxial graphene should be the material of choice for quantum resistance metrology.

The results on material independence are the strongest evidence so far for the hypothesis that the resistance is quantized in units of h/Ne^2 , and thereby support the pending redefinition of the SI units for kilogram and ampere in terms of Planck's constant (h) and the electron charge (e).

2 Conclusions and outlook

In this review we have presented recent progress and trends in device applications of graphene on SiC, produced by thermal decomposition of the substrate. Although promising, graphene-based electronics faces many obstacles before it can become a competitive technology. One of the issues related to a large scale production is the control of variability from device to device, which is mainly related to the intrinsic non uniformities of large area SiC substrates. It is, in fact, a challenge of all graphene production methods intended for electronic applications, because individually derived graphene flakes and transferred foils are not fully reproducible. The fundamental problem of absence of an energy band-gap is a topic of much research effort but still remains unresolved to a sufficient level. It is already demonstrated, that applications of graphene as Tunnel Field-Effect Transistors with I_{on}/I_{off} ratios exceeding 10^4 , high mobility channels for post Si-CMOS applications, SGFET with transconductive sensitivity above 1 mS/V as well as RF-FET with cutoff frequency above 350 GHz can be quite competitive with other material systems, like classical semiconductors.

Graphene-based gas sensors allow the ultimate sensitivity such that the adsorption of individual gas molecules could be detected. Large arrays of such sensors would increase the detection area, allowing higher sensitivity for short-time exposures and the detection of active (toxic) gasses in minute concentrations. Although resistive epitaxial graphene sensors have now been proven to be very sensitive the integration of a graphene layer as the channel in a gas sensitive FET device would maximize the potential of epitaxial graphene as a viable gas sensing film. Graphene on SiC FETs are usually top gated with a dielectric deposited on top of a graphene channel. To allow for gas interaction with the epitaxially grown graphene, a new type of field effect transistor device must be developed e.g. back gated devices.

Graphene-based biosensors are more than sufficiently sensitive to detect the lower limit of hCG hormone in clinical samples.

Recent progress in growth of graphene with high carrier mobilities, together with smart device designs is expected to further utilize the substantial advantages of epitaxial graphene for electronic applications. Progress in this direction relies on the advance of well-controlled growth technologies which can enable thickness uniformity of the graphene layer as well as reproducible mobility and carrier concentration at wafer scale SiC (>100 mm in diameter). Use of novel substrates, e. g. 3C SiC, to enhance graphene quality, is a promising technological path. Continuous exploration of unique physical phenomena, will increase the potential of graphene on SiC technology for microelectronics far beyond quantum metrology which is the most established application area of this graphene to date.

Surface engineering of graphene is one of the roads to produce graphene-based structures utilizing the unique graphene properties, e.g. ballistic transport for high speed devices. Unresolved tasks for graphene transistors include opening a substantial band-gap in graphene, fabricating large-area graphene transistors that operate in the current-saturation regime and engineering graphene nanoribbons with small and well-defined widths.

Precise control of monolayer graphene and manipulation of the interface, for example, elimination of buffer layer and doping with appropriate elements, are crucial for novel microelectronics applications.

Uncited references

[47]; [111].

Acknowledgements

The research leading to these results has received funding from the [European Union Seventh Framework Program](#) under grant agreement n°[604391](#) Graphene Flagship. RY would like to acknowledge [Swedish Research Council](#) for financial support via contracts VR 621-2014-5805 and the LiU Linnaeus Grant.

References

[1]
K.I. Bolotin, K.J. Sikes, Z. Jiang, M. Klima, G. Fudenberg, J. Hone, et al., Ultrahigh electron mobility in suspended graphene, *Solid State Commun.* **146**, 2008, 351–355.

[2]
X. Du, I. Skachko, A. Barker and E.Y. Andrei, Approaching ballistic transport in suspended graphene, *Nat. Nanotechol.* **3**, 2008, 491–495.

[3]
F. Schwierz, Graphene transistors, *Nat. Nano* **5**, 2010, 487–496.

[4]
A.A. Balandin, Thermal properties of graphene and nanostructured carbon materials, *Nat. Mater.* **10**, 2011, 569–581.

[5]
K.S. Novoselov, A.K. Geim, S.V. Morozov, D. Jiang, Y. Zhang, S.V. Dubonos, et al., Electric field effect in atomically thin carbon films, *Science* **306**, 2004, 666–669.

[6]
A.K. Geim and K.S. Novoselov, The rise of graphene, *Nat. Mater.* **6**, 2007, 183–191.

[7]
S. Adam, E.H. Hwang, V.M. Galitski and S.D. Sarma, A self-consistent theory for graphene transport, *Proc. Natl. Acad. Sci. U. S. A.* **104**, 2007, 18392–18397.

[8]
J.-H. Chen, C. Jang, M. Ishigami, S. Xiao, W.G. Cullen, E.D. Williams, et al., Diffusive charge transport in graphene on SiO₂, *Solid State Commun.* **149**, 2009, 1080–1086.

[9]
J.-H. Chen, C. Jang, X. Shudong, M. Ishigami and M.S. Fuhrer, Intrinsic and extrinsic performance limits of graphene devices on SiO₂, *Nat. Nanotechol.* **3**, 2008, 206–209.

[10]

K. Nomura and A.H. MacDonald, Quantum hall ferromagnetism in grapheme, *Phys. Rev. Lett.* **96**, 2006, 256602.

[11]

W. Zhu, V. Perebeinos, M. Freitag and P. Avouris, Carrier scattering, and electrostatic potential in monolayer, bilayer, and trilayer graphene, *Phys. Rev. B* **80**, 2009, 235402.

[12]

M.I. Katsnelson and A.K. Geim, Electron scattering on microscopic corrugations in graphene, *Philos. Trans. R. Soc. A* **366**, 2008, 195–204.

[13]

D.B. Farmer, V. Perebeinos, Y.-M. Lin, C. Dimitrakopoulos and P. Avouris, Charge trapping and scattering in epitaxial graphene, *Phys. Rev. B* **84**, 2011, 205417.

[14]

T. Ando, Screening effect and impurity scattering in monolayer graphene, *J. Phys. Soc. Jpn.* **75**, 2006, 074716.

[15]

J.-H. Chen, C. Jang, S. Adam, M.S. Fuhrer, E.D. Williams and M. Ishigami, Charged-impurity scattering in graphene, *Nat. Phys.* **4**, 2008, 377–381.

[16]

S. Sonde, F. Giannazzo, C. Vecchio and R. Yakimova, Role of graphene/substrate interface on the local transport properties of the two-dimensional electron gas, *Appl. Phys. Lett.* **97** (13), 2010, 132101.

[17]

F. Giannazzo, S. Sonde, R. Lo Nigro, E. Rimini and V. Raineri, Mapping the density of scattering centers limiting the electron mean free path in graphene, *Nano Lett.* **11** (11), 2011, 4612–4618.

[18]

T.O. Wehling, S. Yuan, A.I. Lichtenstein, A.K. Geim and M.I. Katsnelson, Resonant scattering by realistic impurities in graphene, *Phys. Rev. Lett.* **105**, 2010, 056802.

[19]

D.V. Badami, Graphitization of α -silicon carbide, *Nature* **193**, 1962, 569–570.

[20]

A.J. Van Bommel, J.E. Crombeen and A. Van Tooren, LEED and auger electron observations of the SiC(0001) surface, *Surf. Sci.* **48**, 1975, 463–472.

[21]

I. Forbeaux, J-M Themlin, A. Charrier, F. Thibaudau and J.-M. Debever, Solid-state graphitization mechanisms of silicon carbide 6H-SiC polar faces, *Appl. Surf. Sci.* **162/163**, 2000, 406–412.

[22]

C. Berger, Z. Song, T. Li, X. Li, A.Y. Ogbazghi, R. Feng, et al., Ultrathin epitaxial graphite: 2D Electron gas propertieess and a route toward graphene-based nanoelectronics, *J. Phys. Chem. B* **108** (52), 2004, 19912–19916.

[23]

K.V. Emtsev, F. Speck, Th. Seyller, L. Ley and J.D. Riley, Interaction, growth, and ordering of epitaxial graphene on SiC {0001} surfaces: a comparative photoelectron spectroscopy study, *Phys. Rev. B* **77**, 2008, 155303.

[24]

J.B. Hannon, M. Copel and R.M. Tromp, Direct measurement of the growth mode of graphene on SiC(0001) and SiC(0001⁻), *Phys. Rev. Lett.* **107**, 2011, 166101.

[25]

C. Riedl, U. Starke, J. Bernhardt, M. Franke and K. Heinz, Structural properties of the graphene-SiC(0001) interface as a key for the preparation of homogeneous large-terrace graphene surfaces, *Phys. Rev. B* **76**, 2007, 245406.

[26]

A.C. Ferrari, F. Bonaccorso, V. Fal'ko, K.S. Novoselov, S. Roche, P. Bøggild, et al., Science and technology roadmap for graphene, related two-dimensional crystals, and hybrid systems, *Nanoscale* **7**, 2015, 4587–5062.

[27]

S. Tanaka, K. Morita and H. Hibino, Anisotropic layer-by-layer growth of graphene on vicinal SiC(0001) surfaces, *Phys. Rev. B* **81**, 2010, 141406R.

[28]

A. Tzelenchuk, S. Lara-Avila, A. Kalaboukhov, S. Paolilo, M. Syväjärvi, R. Yakimova, et al., Towards a quantum resistance standard based on epitaxial graphene, *Nat. Nanotechnol.* **5** (3), 2010, 186–189.

[29]

F. Hiebel, P. Mallet, F. Varchon, L. Magaud and J.-Y. Veuillen, Graphene-substrate interaction on 6H-SiC(0001): a scanning tunneling microscopy study, *Phys. Rev. B* **78**, 2008, 153412.

[30]

R. Colby, M.L. Bolen, M.A. Capano and E.A. Stach, Amorphous interface layer in thin graphite films grown on the carbon face of SiC, *Appl. Phys. Lett.* **99**, 2011, 101904.

[31]

X. Weng, J. Robinson, K. Trumbull, R. Cavaleiro, M. Fanton and D. Snyder, Structure of few-layer epitaxial graphene on 6H-SiC (0001) at atomic resolution, *Appl. Phys. Lett.* **97**, 2010, 201905.

[32]

G. Nicotra, I. Deretzis, M. Scuderi, C. Spinella, P. Longo, R. Yakimova, F. Giannazzo and A. La Magna, Interface disorder probed at the atomic scale for graphene grown on the C face of SiC, *Phys. Rev. B* **91**, 2015, 155411.

[33]

C. Bouhafs, V. Darakchieva, I.L. Persson, A. Tiberj, P.O.Å. Persson, M. Paillet, A.-A. Zahab, P. Landois, S. Juillaguet, S. Schöche, M. Schubert and R. Yakimova, Structural properties and dielectric function of graphene grown by high-temperature sublimation on 4H-SiC(000-1), *J. Appl. Phys.* **117**, 2015, 085701.

[34]

M. Ostler, I. Deretzis, S. Mammadov, F. Giannazzo, G. Nicotra, C. Spinella, Th. Seyller and A. La Magna, Direct growth of quasi-free-standing epitaxial graphene on nonpolar SiC surfaces, *Phys. Rev. B* **88**, 2013, 085408.

[35]

R.G. Yazdı, R. Vasiliauskas, T. Iakimov, Z. Zakharov, M. Syväjärvi and R. Yakimova, Growth of large area monolayer graphene on 3C-SiC and a comparison with other SiC polytypes, *Carbon* **57**, 2013, 477–484.

[36]

J.A. Robison, K.A. Trumbull, M. LaBella, R. Cavaleiro, M.J. Hollander, M. Zhu, et al., Effect of substrate orientation on the structural and electronic properties of epitaxial graphene on SiC(0001), *Appl. Phys. Lett.* **98**, 2011, 222109.

[37]

G. Nicotra, Q.M. Ramasse, I. Deretzis, A. La. Magna, C. Spinella and F. Giannazzo, Delaminated graphene at silicon carbide facets: atomic scale imaging and spectroscopy, *ACS Nano* **7** (4), 2013, 3045–3052.

[38]

F. Giannazzo, I. Deretzis, A. La Magna, F. Roccaforte and R. Yakimova, Electronic transport at monolayer-bilayer junctions in epitaxial graphene on SiC, *Phys. Rev. B* **86**, 2012, 235422.

[39]

C. Vecchio, S. Sonde, C. Bongiorno, M. Rambach, R. Yakimova, V. Raineri and F. Giannazzo, Nanoscale structural characterization of epitaxial graphene grown on off-axis 4H-SiC (0001), *Nanoscale Res. Lett.* **6**, 2011, 269.

[40]

J. Eriksson, R. Pearce, T. Iakimov, C. Virojandara, D. Gogova, M. Andersson, et al., The influence of substrate morphology on thickness uniformity and unintentional doping of epitaxial graphene on SiC, *Appl. Phys. Lett.* **100**, 2012, 241607.

[41]

W. Strupinski, K. Grodecki, A. Wyszomolek, R. Stepniowski, T. Szkopek, P.E. Gaskell, et al., Graphene epitaxy by chemical vapor deposition on SiC, *Nano Lett.* **11**, 2011, 1786–1791.

[42]

S. Kataria, S. Wagner, J. Ruhkopf, A. Gahoi, H. Pandey, R. Bornemann, et al., Chemical vapor deposited graphene: from synthesis to applications, *Phys. Status Solidi A* **211** (11), 2014, 2439–2449.

[43]

P. Dabrowski, M. Rogala, I. Wlasny, Z. Klusek, M. Kopciuszynski, M. Jalochoowski, W. Strupinski and J.M. Baranowski, Nitrogen doped epitaxial graphene on 4H-SiC(0001) – experimental and theoretical study, *Carbon* **94**, 2015, 214–223.

[44]

A.L. Elias, J.C. Carrero-Sanchez, H. Terrones, M. Endo, J.P. Laclette and M. Terrones, Viability studies of pure carbon- and nitrogen-doped nanotubes with *Entamoeba histolytica*: from amoebicidal to biocompatible structures, *Small* **3**, 2007, 1723–1729.

[45]

J.C. Carrero-Sanchez, L. Eliasa, R. Mancilla, G. Arrellin, H. Terrones, J.P. Laclette, et al., Biocompatibility and toxicological studies of carbon nanotubes doped with nitrogen, *Nano Lett.* **6**, 2006, 1609–1616.

[46]

R. Ribeiro-Palau, F. Lafont, J. Brun-Picard, D. Kazazis, A. Michon, F. Cheynis, et al., Quantum Hall resistance standard in graphene devices under relaxed experimental conditions, *Nat. Nanotechnol.* **10**, 2015, 965–971.

[47]

A.K. Geim, Graphene: status and prospects, *Science* **324**, 2009, 1530–1534.

[48]

P. Avouris and C. Dimitrakopoulos, Graphene: synthesis and applications, *Mater. Today* **15** (3), 2012, 86–97.

[49]

A.H. Castro Neto, F. Guinea, N.M.R. Peres, K.S. Novoselov and A.K. Geim, The electronic properties of graphene, *Rev. Mod. Phys.* **81**, 2009, 109.

[50]

International Technology Roadmap for Semiconductor, 2007, [Online]. Available: <http://public.itrs.net>.

[51]

X. Li, X. Wang, L. Zhang, S. Lee and H. Dai, Chemically derived, ultrasmooth graphene nanoribbon semiconductors, *Science* **319** (5867), 2008, 1229–1232.

[52]

Y.-W. Son, M.L. Cohen and S.G. Louie, Energy gaps in graphene nanoribbons, *Phys. Rev. Lett.* **97**, 2006, 216803.

[53]

T. Ohta, A. Bostwic, T. Seyller, K. Horn and E. Rotenberg, Controlling the electronic structure of bilayer graphene, *Science* **313** (5789), 2006, 951–954.

[54]

G. Fiori and G. Iannaccone, On the possibility of tunable-gap bilayer graphene FET, *IEEE Electron Dev. Lett.* **30** (3), 2009, 261–264.

[55]

Y.Q. Wu, P.D. Ye, M.A. Capano, Y. Xuan, Y. Sui, M. Qi and J.A. Cooper, Top-gated graphene field-effect-transistors of SiC, *Appl. Phys. Lett.* **92** (9), 2008, 092192.

[56]

G. Fiori and G. Iannaccone, Simulation of graphene nanoribbon field-effect transistors, *IEEE Electron Dev. Lett.* **28** (8), 2007, 760–762.

[57]

S.Y. Zhou, G.H. Gweon, A.V. Fedorov, P.N. First, W.A. Heer, D.H. Lee, et al., Substrate-induced bandgap opening in epitaxial graphene, *Nat. Mater.* **6** (10), 2007, 770–775.

[58]

J. Kedzierski, P.-L. Hsu, P. Healey, P. Wyatt, C. Keast, M. Sprinkle, et al., Epitaxial graphene transistors on SiC substrates, *IEEE Trans. Electron Dev.* **55** (8), 2008, 2078–2085.

[59]

K. Yoh, K. Konishi and H. Hibino, Epitaxial graphene FETs with high on/off ratio grown on 4H-SiC, In: *IEEE Conf. on Nanotechnol. (IEEE-NANO)*, 2009, 334–336.

[60]

M. Cheli, P. Michetti and G. Iannaccone, Model and performance evaluation of field-effect transistors based on epitaxial graphene on SiC, *IEEE Trans. Electron Dev.* **57** (8), 2010, 1936–1941.

[61]

P. Michetti, M. Cheli and G. Iannaccone, Model of tunneling transistors based on graphene on SiC, *Appl. Phys. Lett.* **96** (13), 2010, 133508.

[62]

E. Sano and T. Otsuji, Source and drain structures for suppressing ambipolar characteristics of graphene field-effect transistors, *Appl. Phys. Express* **2** (6), 2009, 061601.

[63]

K. Majumdar, K.V.R.M. Murali, N. Bhat, F. Xia and Y.-M. Lin, High on-off ratio bilayer graphene complementary field effect transistors, In: *Proc. IEEE Int. Electron Dev. Meet. (IEDM 2010)*, 2010, IEEE, 32.4.1-4.

[64]

Y. Nagahisa, Y. Harada and E. Tokumitsu, Unipolar behaviour in graphene-channel field-effect-transistors with n-type doped SiC source/drain regions, *Appl. Phys. Lett.* **103**, 2013, 223503.

[65]

S. Hertel, D. Waldmann, J. Jobst, A. Albert, M. Albrecht, S. Reshanov, et al., Tailoring the graphene/silicon carbide interface for monolithic wafer-scale electronics, *Nat. Commun.* **3**, 2012, 557–563.

[66]

D. Waldmann, J. Jobst, F. Speck, T. Seyller, M. Krieger and H.B. Weber, Bottom-gated epitaxial graphene, *Nat. Mater.* **10**, 2011, 357–360.

[67]

P.D. Ye, InGaAs and graphene as high mobility channels for post Si-CMOS applications, In: *IEEE Intern. Conf. on Electron Dev. and Solid-state Circuits*, 2008, 1–5.

[68]

W.S. Hwang, P. Zhao, K. Tahy, L.O. Nyakiti, V.D. Wheeler, R.L. Myers-Ward, et al., Graphene nanoribbon field-effect transistors on wafer-scale epitaxial graphene on SiC substrates, *ApPL Mater.* **3**, 2015, 011101.

[69]

P. Avouris, Z. Chen and V. Perebeinos, Carbon-based electronics, *Nat. Nano* **2**, 2007, 605–615.

[70]

F. Schwierz, Graphene transistors, *Nat. Nanotechnol.* **5**, 2010, 487–496.

[71]

Y. Wu, Y.-M. Lin, A.A. Bol, K.A. Jenkins, F. Xia, D.B. Farmer, Y. Zhu, et al., High-frequency, scaled graphene transistors on diamond-like carbon, *Nature* **472**, 2011, 74–78.

[72]

J.S. Moon, D. Curtis, M. Hu, D. Wong, C. McGuire, P.M. Campbell, et al., Epitaxial-graphene RF field-effect transistors on Si-face 6H-SiC substrates, *IEEE Electron Dev. Lett.* **30** (6), 2009, 650–652.

[73]

Y.-M. Lin, C. Dimitrakopoulos, K.A. Jenkins, D.B. Farmer, H.-Y. Chiu, A. Grill, et al., 100-GHz transistors from wafer-scale epitaxial graphene, *Science* **327** (5966), 2010, 662.

[74]

Y.Q. Wu, D.B. Farmer, A. Valdes-Garcia, W.J. Zhu, K.A. Jenkins, C. Dimitrakopoulos, et al., Record high RF performance for epitaxial graphene transistors, *IEDM Tech. Dig.* **23** (8), 2011, 1–3.

[75]

Y. Wu, K.A. Jenkins, A. Valdes-Garcia, D.B. Farmer, Y. Zhu, et al., State-of-the-art graphene high-frequency electronics, *Nano Lett.* **12** (6), 2012, 3062–3067.

[76]

H.K. Gummel, A self-consistent iterative scheme for one-dimensional steady state transistor calculations, *IEEE Trans. Elect. Dev. ED-II* **11** (10), 1964, 455–465.

[77]

S.-J. Han, K.A. Jenkins, A.V. Garcia, A.D. Franklin, A.A. Bol and W. Haensch, High-frequency graphene voltage amplifier, *Nano Lett.* **11** (9), 2011, 3690–3693.

[78]

X. Yang, G. Liu, A.A. Balandin and K. Mohanram, Triple-mode single-transistor graphene amplifier and its applications, *ACS Nano* **4**, 2010, 5532–5538.

[79]

H. Wang, A. Hsu, J. Wu, J. Kong and T. Palacios, Graphene-based ambipolar RF mixers, *IEEE Electron Dev. Lett.* **31** (9), 2009, 906–908.

[80]

Y.-M. Lin, A. Valdes-Garcia, S.-J. Han, D.B. Farmer, I. Neric, Y. Sun, et al., Wafer-scale graphene integrated circuit, *Science* **332** (6035), 2011, 1294–1297.

[81]

J.-S. Moon, D.K. Gaskill and P. Asbeck, Recent advances in graphene RF electronics: opportunities, *ECS Trans.* **53** (1), 2013, 83–89.

[82]

H. Madan, M.J. Hollander, J.A. Robinson and S. Datta, Graphene transistors for ambipolar mixing at microwave frequencies, *ECS Trans.* **53** (1), 2013, 91–100.

[83]

S. Hertel, M. Krieger and H.B. Weber, Monolithic circuits with epitaxial graphene/silicon carbide transistors, *Phys. Status Solidi RRL* **8** (8), 2014, 688–691.

[84]

E.H. Hall, On a new action of the magnet on electric currents, *Am. J. Math.* **2** (3), 1979, 287–292.

[85]

G. Masson, D. Frachon, T. Dorge, Y. Ronnat and R. Arlot, A new generation of contactless magnetic position sensors, *Sens. Lett.* **7** (3), 2009, 451–455.

[86]

Z. Bing, X. Du and J. Sun, Control of three-phase PWM rectifiers using a single DC current sensor, *IEEE Trans. Power Electron* **26** (6), 2011, 1800–1808.

[87]

A. Simpkins and E. Todorov, Position estimation and control of compact BLDC motors based on analogue linear Hall effects sensors, In: *Proc. of the Am. Control Conf*, 2010, 1948–1955.

[88]

H. Xu, Z. Zhang, R. Shi, H. Liu, Z. Wang, S. Wang, et al., Batch fabricated high-performance graphene Hall elements, *Sci. Rep.* **3**, 2013, 1207.

[89]

V. Panchal, K. Cedergren, R. Yakimova, A. Tzalenchuk, S. Kubaktin and O. Kazakova, Small epitaxial graphene devices for magnetosensing applications, *J. Appl. Phys.* **111**, 2012, 07E509.

[90]

R. Yakimova, T. Iakimov, M. Syväjärvi, Process for growth of graphene, US2013/0171347 A1, Jul. 4, 2013.

[91]

O. Kazakova, V. Panchal, J. Gallop, P. See, D.C. Cox, M. Spasova and L.F. Cohen, Ultrasmall particle detection using a submicron Hall sensor, *J. Appl. Phys.* **107**, 2010, 09E708.

[92]

L.D. Michele, C. Shelly, J. Gallop and O. Kazakova, Single particle detection: phase control in submicron Hall sensors, *J. Appl. Phys.* **108**, 2010, 103918.

[93]

L.D. Michele, C. Shelly, P. Marco, P. See, D. Cox and O. Kazakova, Detection and susceptibility measurements of a single Dynal bead, *J. Appl. Phys.* **110**, 2011, 063916.

[94]

C.-C. Tang, M.-Y. Li, L.J. Li, C.C. Chi and J.C. Chen, Characteristics of a sensitive micro-Hall probe fabricated on chemical vapor deposited graphene over the temperature range from liquid-helium to room temperature, *Appl. Phys. Lett.* **99**, 2011, 112107.

[95]

T. Ciuk and W. Strupinski, Statistics of epitaxial graphene for Hall effect sensors, *Carbon* **93**, 2015, 1042–1049.

[96]

C. Chua, M. Connolly, A. Lartsev, T. Yager, S. Lara-Avila, S. Kubatkin, et al., Quantum Hall effect and quantum point contact in bilayer-patched epitaxial graphene, *Nano Lett.* **14** (6), 2014, 3369–3373.

[97]

T. Ciuk, S. Cakmakyapan, E. Ozbay, P. Caban, K. Grodecki, A. Krajewska, et al., Step-edge-induced resistance anisotropy in quasi-free-standing bilayer chemical vapor deposition graphene on SiC, *J. Appl. Phys.* **116**, 2014, 123708.

[98]

X. Cai, A.B. Sushkov, R.J. Suess, M.M. Jadidi, G.S. Jenkins, L.O. Nyakiti, et al., Sensitive room-temperature terahertz detection via the photothermoelectric effect in graphene, *Nat. Nanotechnol.* **9**, 2014, 814–819.

[99]

T.J. Anderson, K.D. Hobart, J.D. Greenlee, D.I. Shahin, A.D. Koehler, M.J. Tadjer, et al., Ultraviolet detector based on graphene/SiC heterojunction, *Appl. Phys. Express* **8**, 2015, 041301.

[100]

F. Schedin, A.K. Geim, S.V. Morozov, E.W. Hill, P. Blake, M.I. Katsnelson and K.S. Novoselov, Detection of individual gas molecules adsorbed on graphene, *Nat. Mater.* **6**, 2007, 652–655.

[101]

G. Liu, W. Stillman, S. Rumyantsev, Q. Shao, M. Shur and A.A. Balandin, Low-frequency electronic noise in the double-gate single-layer graphene transistors, *Appl. Phys. Lett.* **95**, 2009, 033103.

[102]

R. Pearce, T. Iakimov, M. Andersson, L. Hultman, A.L. Spetz and R. Yakimova, Epitaxially grown graphene based gas sensors for ultra-sensitive NO₂ detection, *Sens. Actuat. B* **155**, 2011, 451–455.

[103]

M.V.S. Chandrashekhara, J. Lu, M.G. Spencer, M. Qazi and G. Koley, Large area nanocrystalline graphite films on SiC for gas sensing applications, In: *Proc. of IEEE Conf. of sens., Atlanta, GA, USA*, 2007, 558–561.

[104]

R. Pearce, J. Eriksson, T. Iakimov, L. Hultman, A.L. Spetz and R. Yakimova, On the differing sensitivity to chemical gating of single and double layer epitaxial graphene explored using scanning Kelvin probe microscopy, *ACS Nano* **7** (5), 2013, 4647–4656.

[105]

R.E. Hill-Pearce, V. Eles, A. Lartsev, N.A. Martin, I.B. Snook, J.J. Helmore, et al., The effect of bilayer regions on the response of epitaxial graphene devices to environmental gating, *Carbon* **93**, 2015, 896–902.

[106]

J. Eriksson, unpublished.

[107]

T. Yager, A. Lartsev, S. Mahashabde, S. Charpentier, D. Davidovikj, A. Danilov, et al., Express optical analysis of epitaxial graphene on SiC: impact of morphology on quantum transport, *Nano Lett.* **13** (9), 2013, 4217–4223.

[108]

I.G. Ivanov, J.U. Hassan, T. Iakimov, A.A. Zakharov, R. Yakimova and E. Janzén, Layer-number determination in graphene on SiC by reflectance mapping, *Carbon* **77**, 2014, 492–500.

[109]

A.D. Bartolomeo, Graphene Schottky Diodes: an Experimental Review of the Rectifying Graphene/semiconductor Heterojunction, arXiv: 1505.07686 [cond-mat.mess- hall]2015.

[110]

S. Kopylov, A. Tzalenchuk, S. Kubatkin and V.I. Fal'ko, Charge transfer between epitaxial graphene and silicon carbide, *Appl. Phys. Lett.* **97**, 2010, 112109.

[111]

S. Sonde, F. Giannazzo, V. Raineri, R. Yakimova, J.-R. Huntzinger, A. Tiberj, et al., Electrical properties of the graphene/4H-SiC (0001) interface probed by scanning current spectroscopy, *Phys. Rev. B* **80**, 2009, 241406–241409.

[112]

P.K. Ang, W. Chen, A.T.S. Wee and K.P. Loh, Solution-gated epitaxial graphene as pH sensor, *Am. Chem. Soc.* **130** (44), 2008, 14392–14393.

[113]

T. Cohen-Karni, Q. Qing, Q. Li, Y. Fang and C.M. Lieber, Graphene and nanowire transistors for cellular interfaces and electrical recording, *Nano Lett.* **10** (3), 2010, 1098–1102.

[114]

L.H. Hess, M.V. Hauf, M. Seifert, F. Speck, T. Seyller, M. Stutzmann, et al., High-transconductance graphene solution-gated field effect transistors, *Appl. Phys. Lett.* **99**, 2011, 033503.

[115]

K.V. Emstev, A. Bostwick, K. Horn, J. Jobst, G.L. Kellogg, L. Ley, et al., Towards wafer-size graphene layers by atmospheric pressure graphitization on silicon carbide, *Nat. Matter* **8**, 2009, 203–207.

[116]

G. Steinhoff, B. Baur, G. Wrobel, S. Ingebrandt, A. Offenhäusser, A. Dadgar, et al., Recording of cell action potentials with AlGaIn/GaN field-effect transistors, *Appl. Phys. Lett.* **86**, 2005, 033901–033903.

[117]

J.A. Garido, A. Härtl, S. Kuch, M. Stutzmann, O.A. Williams and R.B. Jackmann, pH sensors based on hydrogenated diamond surfaces, *Appl. Phys. Lett.* **86**, 2005, 073504.

[118]

C. Sprössler, M. Denyer, S. Britland, W. Knoll and A. Offenhäusser, Electrical recordings from rat cardiac muscle cells using field-effect transistors, *Phys. Rev. E* **60** (2), 1999, 2171.

[119]

P.E. Erden and E. Kiliç, A review of enzymatic uric acids biosensors based on amperometric detection, *Talanta* **107**, 2013, 312–323.

[120]

P. Bobby and R.D. Marco, Impedance spectroscopy: over 35 years of electrochemical sensor optimization, *Electrochem. Acta* **51** (28), 2006, 6217–6229.

[121]

S. Teixeira, G. Burwell, A. Castaing, D. Gonzalez, R.S. Conlan and O.J. Guy, Epitaxial graphene immunosensor for human chorionic gonadotropin, *Sens. Actuat. B* **190**, 2014, 723–729.

[122]

K.V. Klitzing, G. Dorda and M. Pepper, New method for high-accuracy determination of the fine-structure constant based on quantized Hall resistance, *Phys. Rev. Lett.* **45**, 1980, 494–497.

[123]

F. Delahaye and B. Jeckelmann, Revised technical guidelines for reliable dc measurements of the quantized Hall resistance, *Metrologia* **40** (5), 2003, 217–223.

[124]

T.J.B.M. Janssen, J.M. Williams, N.E. Fletcher, R. Goebel, A. Tzalenchuk, R. Yakimova, et al., Precision comparison of the quantum Hall effect in graphene and gallium arsenide, *Metrologia* **49** (3), 2013, 294–306.

[125]

A. Tzalenchuk, S. Lara-Avila, K. Cedergren, M. Syväjärvi, R. Yakimova, O. Kazakova, et al., Engineering and metrology of epitaxial graphene, *Solid State Commun.* **151**, 2011, 1094–1099.

[126]

K.S. Novoselov, Z. Jiang, Y. Zhang, S.V. Morozov, H.L. Stormer, U. Zeitler, et al., Room-temperature quantum Hall effect in grapheme, *Science* **315**, 2007, 1379–1379.

[127]

W. Poirier and F. Schopfer, Resistance metrology based on the quantum Hall effect, *Eur. Phys. J. Spec. Top.* **171**, 2009, 207–245.

[128]

J.A. Alexander-Webber, A.M.R. Baker, T.J.B.M. Janssen, A. Tzalenchuk, S. Lara-Avila, S. Kubatkin, et al., Phase space for the breakdown of the quantum Hall effect in epitaxial graphene, *Phys. Rev. Lett.* **111**, 2013, 096601.

[129]

T.J.B.M. Janssen, N.E. Fletcher, R. Goebel, J.M. Williams, A. Tzalenchuk, R. Yakimova, et al., Graphene, universality of the quantum Hall effect and redefinition of the SI system, *New J. Phys.* **13**, 2011, 093026.

[130]

A. Satrapinski, S. Novikov and N. Lebedeva, Precision quantum Hall resistance measurement on epitaxial graphene device in low magnetic field, *Appl. Phys. Lett.* **103**, 2013, 173509.

[131]

C. Virojanadara, M. Syväjärvi, R. Yakimova, L. Johansson, A.A. Zakharov and T. Balasubramanian, Homogeneous large-area graphene layer growth on 6H-SiC(0001), *Phys. Rev. B* **78**, 2008, 245403.

[132]

R. Yakimova, C. Virojanadara, D. Gogova, M. Syväjärvi, D. Siche, K. Larsson, et al., Analysis of the formation conditions for large area epitaxial graphene on SiC substrates, *Mater. Sci. Forum* **645–648**, 2010, 565–568.

Highlights

- Graphene-based sensors with ultimate sensitivity of individual gas molecules.
- Graphene-based biosensors sufficiently sensitive to detect the lower limit of HCG hormones in clinical samples.
- Novel quantum Hall resistance standard with higher performance.

Query: Please note that author's telephone/fax numbers are not published in Journal articles due to the fact that articles are available online and in print for many years, whereas telephone/fax numbers are changeable and therefore not reliable in the long term.

Answer: I agree

Query: Please provide the grant number for: 1) Swedish Research Council, if any.

Answer: VR 621-2014-5805

Query: Uncited references: This section comprises references that occur in the reference list but not in the body of the text. Please position each reference in the text or, alternatively, delete it. Any reference not dealt with will be retained in this section. Thank you.

Answer: Ref.47 is added in the text. Ref. 111 is added in the text.

Query: Please confirm that given names and surnames have been identified correctly.

Answer: Yes, the given names and surnames are correct.

Query: Your article is registered as a regular item and is being processed for inclusion in a regular issue of the journal. If this is NOT correct and your article belongs to a Special Issue/Collection please contact r.laman@elsevier.com immediately prior to returning your corrections.

Answer: Yes, the article is for regular issue.