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Going ballistic: Graphene hot electron transistors

S. Vaziri [a], A.D. Smith [a], M. Östling [a], G. Lupina [b], J. Dabrowski [b], G. Lippert [b], W. Mehr [b,1], F. Driussi [c], S. Venica [c], V. Di Lecce [d], A. Gnudi [d], M. König [e], G. Ruhl [e], M. Belete [f], M. C. Lemme [f,*]

[a] KTH Royal Institute of Technology, School of Information and Communication Technology, Isafjordsgatan 22, 16440 Kista, Sweden
[b] IHP, Im Technologiepark 25, 15236 Frankfurt (Oder), Germany
[c] University of Udine, via delle Scienze 208, 33100 Udine, Italy
[d] E. De Castro Advanced Research Center on Electronic Systems, University of Bologna, Bologna 40135, Italy
[e] Infineon Technologies AG, Wernerwerkstrasse 2, 93049 Regensburg, Germany
[f] University of Siegen, Hölderlinstr. 3, 57076 Siegen, Germany

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ABSTRACT

This paper reviews the experimental and theoretical state of the art in ballistic hot electron transistors that utilize two-dimensional base contacts made from graphene, i.e. graphene base transistors (GBTs). Early performance predictions that indicated potential for THz operation still hold true today, even with improved models that take non-idealities into account. Experimental results clearly demonstrate the basic functionality, with on/off current switching over several orders of magnitude, but further developments are required to exploit the full potential of the GBT device family. In particular, interfaces between graphene and semiconductors or dielectrics are far from perfect and thus limit experimental device integrity, reliability and performance.

1. Introduction

The experimental realization of graphene [1] and other two-dimensional (2D)-materials [2] has opened up new opportunities for pushing the limits of the state-of-the-art in electronics [3,4] and photonics [5,6]. This has been motivated by graphene's excellent material properties, which surpass those of conventional materials in many aspects. Nevertheless, in spite of its high charge carrier mobility [7] and saturation velocity [8], graphene field effect transistors (GFETs) struggle to match or surpass the performance of conventional silicon FETs. Fundamental challenges originate in the electronic band structure of graphene. The absence of a band gap leads to high off-state currents and low on/off current ratios, which prohibit GFET applications as logic gates [9,10]. Another consequence of the zero band gap is band to band tunneling, which reduces the output current saturation and the voltage gain, limiting the RF performance potential of GFETs [11,12]. Recently, vertical electronic device concepts have been proposed to overcome this intrinsic limitation [13–19]. One of these novel device concepts, introduced by Mehr et al. in 2012, is vertical graphene base transistor (GBT) [13]. The concept of the GBT is based on the metal-base hot-electron transistors (HETs) introduced originally by Mead in 1961 [20]. HETs utilize high energy tunneling injected electrons (hot electrons) to reach high performance [21]. The first HETs were composed of metal emitters, metal bases, and metal collectors, which were isolated from each other by thin oxide layers. One of the main challenges for the HETs as well as heterojunction bipolar transistors (HBTs) is that the cutoff frequency is limited by base transit time. While thinning down the base mitigates this issue, it dramatically increases the base resistance, resulting in high RC delay and self-bias crowding. The graphene base transistor, in contrast, exploits the high conductivity and the single atomic-thinness of graphene as the base material in HETs to minimize the base transit time and achieve high cutoff frequencies. This concept is distinctly different from vertical graphene field effect tunneling transistors as introduced by Britnell et al. [16]. While the latter functions due to the limited density of states in single layer graphene and electrostatic gate control of the carrier transport between two isolated single layer graphene (SLG) sheets, the GBT operates through emitter–base barrier modulation analogous to the bipolar technology,. This article reviews the experimental and theoretical progress on the GBTs and related devices.

2. Working principles of the GBT

The difference between the GBT and the GFET is shown schematically in Fig. 1. In the GFET, carrier transport happens in

* Corresponding author.
E-mail address: max.lemme@uni-siegen.de (M.C. Lemme).
[1] Deceased.

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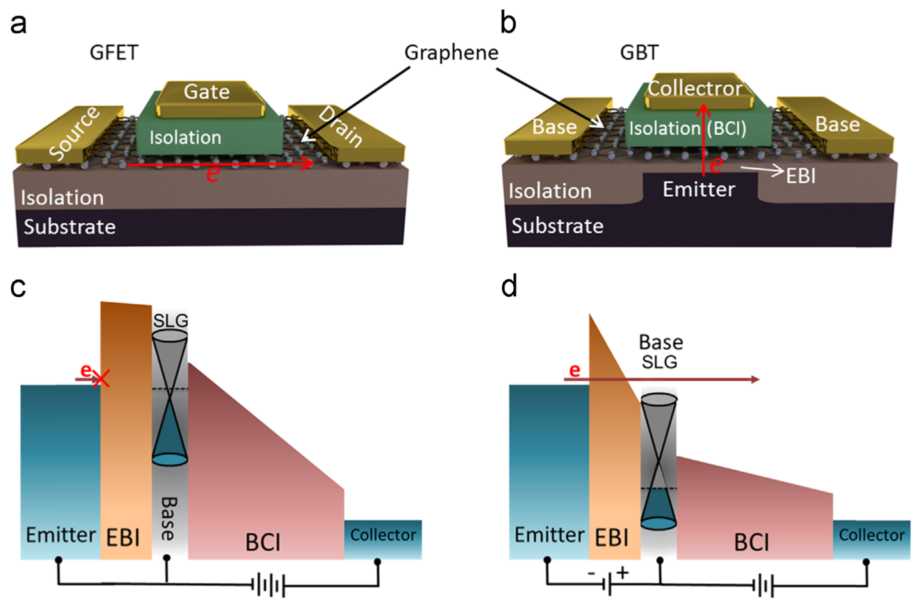

Fig. 1. (Color online) Schematics of (a) GFET and (b) GBT. The red arrow shows the direction of electron transport in the on-state of these devices. (c,d) Simplified band diagram of the GBT in the (c) off-state and (d) on-state in the common-emitter configuration. We note that in (c) and (d) the energy difference between Fermi level and Dirac potential in graphene represents graphene's quantum capacitance effect.

the graphene plane between the source and the drain with a V_{ds} bias, while the gate electrostatically controls the conductivity of the graphene channel (Fig. 1a). In the GBT, in contrast, carriers move perpendicular through the graphene plane. The graphene base is isolated from a metal or doped semiconductor emitter and collector by an emitter–base insulator (EBI) and a base-collector insulator (BCI). Fig. 1c and d illustrates the simplified band diagram of a GBT in the off-state and the on-state, respectively. The GBT collector current can be modulated by the emitter–base voltage, if an appropriate, fixed emitter–collector voltage is applied (common emitter configuration) and if an appropriate electron barrier height and thickness is chosen for the EBI. When the emitter–base voltage is low, electrons cannot be injected and the device is in the off-state (Fig. 1c). When the emitter–base voltage is high, the effective barrier thickness is reduced, enabling electron injection to the graphene base through Fowler–Nordheim tunneling and onwards towards the collector (Fig. 1d). Injected electrons with energies comparable to the emitter Fermi level are considered as hot electrons. Finally, by choosing a low BCI barrier to suppress or minimize quantum mechanical backscattering phenomena at the base-collector interface, the injected hot electrons contribute to the collector on-current, ideally approaching a current gain of 1. Alternatively, EBIs with low barrier heights can facilitate the emission of electrons by thermionic emission (not shown) as a result of effective barrier height lowering. Due to the 2D nature of graphene, hot electron motion through the atomically thin material could approach ideal ballistic transport – resulting in quasi-zero base transit time.

The performance of GBTs strongly depends on the design parameters to maximize the current and minimize the loss mechanisms. Thanks to the one-atom thick graphene, the scattering of hot electrons in the base is already minimized. However, EBI parameters need to be accurately chosen to guarantee high injection current densities. Simultaneously, the EBI needs to prevent the emission of cold electrons with energies comparable to the base Fermi energy via defect mediated electron transport or direct tunneling. These cold electrons are not able to surpass the base-collector barrier and lead to the parasitic base current. Cold electron transport limits the common-base current gain or current transfer ratio α (I_C/I_E). Furthermore, the BCI needs to act as an electron filter, which allows the passage of the hot electrons and blocks the cold electron emission from the base to the collector. This requires a low barrier to minimize the quantum mechanical backscattering of hot electrons at the BCI barrier, and, simultaneously, suppress thermionic, tunneling, and defect mediated electron transport from base to collector. Consequently, modeling of GBTs to define a window of optimized design parameters for high performance operation is essential.

3. Device modeling/simulation and performance projection

A zero-order estimation of the GBT performance has been performed based on quantum-mechanical simulations in [13]. For that purpose, the Schrödinger equation with open-boundary conditions was solved numerically for one-band effective potential rounded up by image force at interfaces with emitter and collector. This early model, with no scattering effects included, predicted that for a terahertz operation at emitter–base voltages around 1 V, an EBI with a barrier of 0.4 eV or smaller and a thickness lower than 3–5 nm is required. Fig. 2 shows simulated transfer and output characteristics for a device with Er_2Ge_3/Ge emitter ($\Phi_{EBI}=0.2$ eV) and a compositionally graded $Ti_xSi_{1-x}O_2$ BCI. Clearly, the device shows switching over several orders of magnitude and saturating output characteristics.

More recent modeling implementations have confirmed the potential of the GBT and explored the design space of the device [22]. Venica et al. have proposed a model that calculates the GBT electrostatics self-consistently with the charge stored in the graphene and the electrons tunneling through the EBI and BCI [23]. In this way, the model accounts for the electrostatic impact of the charge traveling along the GBT. As a result, space charge effects at high current levels (that usually reduce the maximum f_T in bipolar transistors) are considered. Since the physical origin of the base current is still unclear and debated [15], the model assumes a priori a negligible base current and the collector current density (J_C) is thus due to the electrons injected from the emitter.

The model calculates the I–V characteristics and it has been verified through comparison with available experiments (SiO_2 EBI in Fig. 9a). In addition, it estimates f_T by means of a quasi-static