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Towards ballistic vertical transistors by graphene integration with nitride semiconductors

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Summary. — 2D materials integration with group III-nitride semiconductors is currently explored as a platform for novel optoelectronic and ultra-high frequency electronic devices and sensors. In this paper, the Schottky junction formed by graphene and AlGaN/GaN heterostructures has been used as the building block of a graphene-base hot electron transistor potentially able to operate in the THz frequency regime.

1. – Introduction

The integration of two-dimensional (2D) materials with bulk (3D) semiconductors is a promising approach to implement novel device concepts, beyond the limitations imposed by traditional growth techniques [1]. One of the most interesting devices recently enabled by 2D/3D heterostructures is the hot electron transistor (HET), exploiting the vertical ballistic transport of hot electrons across an ultra-thin conductive layer (base) embedded between two insulating films (emitter-base and collector-base barriers) [2]. In particular, graphene (Gr) has been proposed as an ideal base material, as it combines monoatomic thickness, enabling ballistic electron transit in the transversal direction, with excellent in-plane transport properties [3-5]. Theoretical studies have predicted excellent high-frequency performances, with a cut-off frequency (f_T) up to several THz, for Gr base HETs [6]. Besides the ultra-thin base, an emitter-base barrier allowing efficient hot electrons injection is a key element of the HET device. The first examples of Gr HETs, with the emitter-base barrier consisting of a nanometer-thin SiO_2 film on a n^+-doped Si substrate, suffered from a very poor injected current density ($10^{-4} - 10^{-3}$ A/cm^2),

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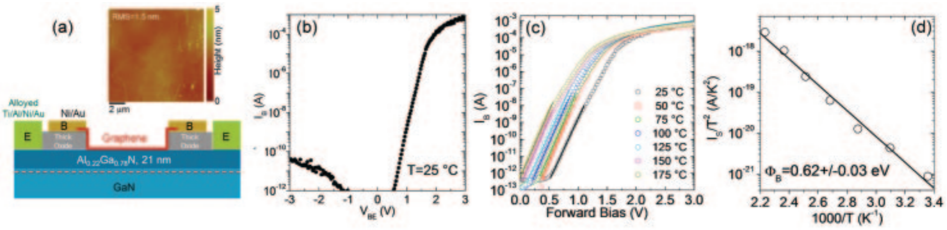

Fig. 1. – (a) Schematic illustration of the Gr/AlGaN/GaN Schottky diode, with an AFM morphology of Gr surface (insert). (b) Typical current-voltage (I-V) characteristic of the diode measured at 25 °C. (c) Forward bias I-V curves at different temperatures in the range from 25 to 175 °C. (b) Arrhenius plot of I_s/T^2 *vs.* $1000/T$, with the evaluation of the Gr/AlGaN Schottky barrier height Φ_B.

mainly due to the energy barrier between Si and SiO_2 [7,8]. More recently, the possibility of implementing HETs with high on-state current by the integration of Gr with group III- nitride semiconductors has been considered [9-12]. In particular, thin films of AlN or $Al_xGa_{1-x}N$, epitaxially grown on GaN, proved to be excellent emitter-base barriers, due to their superior structural quality with respect to oxide layers, and to the presence of high density ($\approx 10^{13}\,cm^{-2}$) two-dimensional electron gas (2DEG), working as the hot electrons emitter, at the AlGaN/GaN interface. Furthermore, the possibility of tailoring both the thickness and the conduction band discontinuity between $Al_xGa_{1-x}N$ and GaN by the Al content (x) allows exploiting different hot electron injection mechanisms, *i.e.*, tunneling through the barrier in the case of few-nanometer thick AlN [10] or Al-rich ($x > 0.5$) $Al_xGa_{1-x}N$ [11], or thermionic emission above the barrier in the case of thicker (>10 nm) $Al_xGa_{1-x}N$ barrier layers (with $x \approx 0.15$–0.3) [12]. Although some initial studies on the direct growth of Gr on AlN or Al-rich AlGaN samples have been reported using high temperature ($\sim$1350 °C) CVD using propane (C_3H_8) as a gas precursor [13,14], the main approach to fabricate high-quality Gr heterostructures with nitrides remains the transfer of Gr grown by CVD on catalytic metals [15].

In this paper, a Gr Schottky junction with a high quality $Al_{0.22}Ga_{0.78}N$/GaN heterostructure has been fabricated by optimized transfer of monolayer Gr to the AlGaN surface, resulting in uniform and conformal coverage. Due to their excellent rectification properties, this Schottky junction has been employed as building blocks of a GBHET with interesting performances, including a wide (six decades) modulation range of the collector current J_C by the base-emitter bias and a high collector current density ($\approx$1 A/cm^2).

2. – Results and discussion

The vertical current injection through the Gr/AlGaN/GaN heterojunction was investigated on properly fabricated diode structures, as schematically illustrated in fig. 1(a). A representative AFM morphology of monolayer Gr transferred onto AlGaN surface is also reported in the insert, showing uniform coverage and low roughness. A typical current-voltage (I-V) characteristic of the diode measured at room temperature is reported in fig. 1(b), showing excellent rectifying behavior, with a very low current under reverse (negative) bias and exponential increase of the current over 8 decades under forward (positive) bias. To further investigate the current injection mechanisms, a T-dependent characterization of the forward bias I-V curves has been carried in the range from 25 to

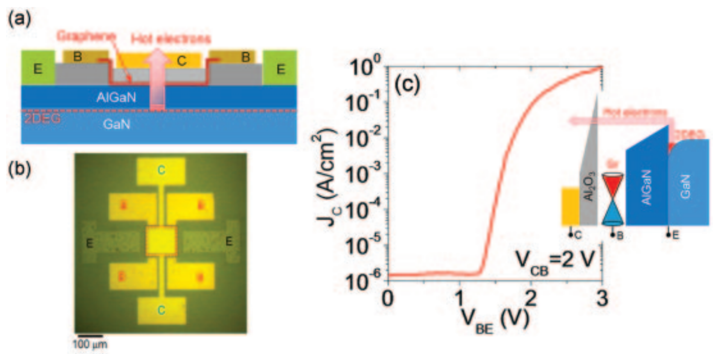

Fig. 2. – Schematic cross-section (a) and top-view optical image (b) of the HET device. (c) Collector current density (J_C) as a function of the emitter-base bias V_{BE}, and for fixed values of $V_B = 0\,\mathrm{V}$ and collector bias $V_{CB} = 2\,\mathrm{V}$. Illustration of the HET band-diagram in the ON-state of the device.

175 °C, as shown in fig. 1(c). The strong dependence of I on T indicates that current transport can be described by the thermionic emission equation $I = I_s \exp(qV/nkT)$, where n is the ideality factor, and $I_s = AA^*T^2 \exp(-q\Phi_B/kT)$ is the saturation current, being A the diode area, A^* the Richardson constant, k the Boltzmann constant, and q the electron charge [12]. For each curve in fig. 1(c), a linear fit was performed in the low-bias region and the term I_s was evaluated as the intercept on the current axis. Figure 1(d) shows the Arrhenius plot of I_s/T^2 *vs.* $1000/T$, from which the Gr/AlGaN Schottky barrier height ($\Phi_B = 0.62 \pm 0.03\,\mathrm{eV}$) was evaluated. Noteworthy, this Φ_B value is much lower than the one expected according the Schottky-Mott theory for an ideal Gr/AlGaN Schottky barrier, *i.e.*, $\Phi_B = W_{Gr} - \chi_{\mathrm{AlGaN}} = 1.9\,\mathrm{eV}$, with $W_{\mathrm{Gr}} = 4.5\,\mathrm{eV}$ the Gr work function and $\chi_{\mathrm{AlGaN}} = 2.6\,\mathrm{eV}$ the electron affinity of $Al_{0.22}Ga_{0.78}N$. This large discrepancy was ascribed to a Fermi level pinning at the interface between Gr and AlGaN [9, 12].

After investigating current injection at the Gr/AlGaN/GaN junction, we fabricated a complete HET structure (schematically illustrated in fig. 2(a)), which included a base-collector barrier, represented by a thin (10 nm) Al_2O_3 film deposited by ALD on top of Gr [16]. A top-view optical microscopy of the HET is also shown in fig. 2(b), where the active area (delimited by the red-dashed line) and the emitter (E), base (B) and collector (C) contacts are indicated. Figure 2(c) shows the collector current density (J_C) as a function of the emitter-base bias (V_{BE} from 0 to 3 V), for fixed values of $V_B = 0$ V and collector bias $V_{CB} = 2$ V. The $J_C - V_{BE}$ characteristic exhibits a low off-state current density $J_{C,OFF} \approx 1\ \mu A/\mathrm{cm}^2$ for $V_{BE} < 1.3\,\mathrm{V}$, due to the leakage current through the Al_2O_3 barrier, and an exponential increase of J_C for $V_{BE} > 1.3\,\mathrm{V}$. This on-state current is associated to the hot electrons injected from the AlGaN/GaN emitter, which ballistically transit through the Gr base, and reach the collector, after Fowler-Nordheim (FN) tunneling through the base-collector barrier, as illustrated in the insert of fig. 2(c). The efficient hot electrons injection at the Gr/AlGaN/GaN heterojunction allows to achieve a ON/OFF current density ratio $J_{C,ON}/J_{C,OFF} \approx 10^6$ with a $J_{C,ON} \approx 1\,\mathrm{A/cm}^2$, mainly limited by the FN tunneling through the Al_2O_3 base-collector barrier. Hence, further improvement in the device performances is expected by adoption of alternative base-collector barriers on Gr with more favorable band alignment.

3. – Conclusion

In conclusion, the electronic transport in Gr/$Al_{0.22}Ga_{0.78}N$/GaN heterostructures has been investigated, showing excellent Schottky diode behavior. This Schottky junction has been employed as building blocks of a GBHET with promising performances for next generation ultra-high-frequency (THz) applications.

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