Graphene vertical heterostructures with wide bandgap semiconductors for energy efficient and high frequency electronics

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In the last years, novel device concepts exploiting vertical current transport in graphene (Gr) heterostructures with ultrathin insulators or semiconductors [1] have been demonstrated, showing ultra-fast operation and on/off current ratios ($>10^4$) not reachable by conventional lateral Gr field effect transistors (FET). One of the main challenges in this field is the development of scalable approaches for the fabrication of these device architectures on wafer scale.
In this context, Gr integration with the technologically mature wide bandgap semiconductors (WBS), such as SiC and III-Nitrides (i.e. GaN and related heterostructures, AlGaN/GaN) can represent the platform for a new class of vertical transistors with extremely low power dissipation in the off-state and high operation frequency (up to THz) in the on-state. In this paper, recent investigations on the structural and electrical properties of Gr heterostructures with SiC and III-Nitrides will be reviewed, and current understanding on the mechanisms of vertical current transport at these heterointerfaces will be discussed.
Controlled graphitization of hexagonal SiC by high temperature thermal processes provides single or few layers of Gr on large area directly on a WBS. The structural properties of this system (number of Gr layers, stacking sequence, epitaxial relation with the substrate) crucially depend on the SiC crystal orientation, as well as on the initial surface morphology. Recent investigations on Gr grown on the polar faces, (0001) and (000-1), of hexagonal SiC and on the low-index non-polar faces, (11-20) and (1-100), will be reviewed [2,3]. Furthermore, the local structural and electrical properties of Gr residing on SiC nanosteps and facets will be discussed, basing on atomic resolution AC-STEM analyses and nanoscale electrical measurements by SPM [4]. These results will be discussed in relation to recent reports on the exceptional ballistic transport in graphene nanoribbons grown on SiC facets [5]. A special focus will be given to the vertical current transport at the interface between epitaxial Gr and SiC (0001) and to the possibility of tailoring the contact properties from Ohmic to Schottky by hydrogen intercalation [6,7].
Different approaches have been recently explored to fabricate Gr heterostructures with III-N layers, including the Gr transfer on GaN or AlGaN/GaN [8,9], the direct CVD growth of Gr on AlN [10], as well as the van der Waals epitaxy of single crystalline GaN on epitaxial Gr on SiC [11]. Among these systems, Gr/AlGaN/GaN heterostructures deserve particular interest, since they offer the possibility to explore a rich physics and to evaluate new device concepts based on the Gr and AlGaN/GaN 2DEGs in close proximity. Vertical current transport across this heterostructure has been recently investigated by high spatial resolution SPM methods (CAFM and SCM), revealing a high spatial uniformity and a low Schottky barrier between Gr and $Al_{025}Ga_{0.75}N$ [8] (see Fig.1), which can be exploited in vertical transistors applications.
Finally, the design, implementation and expected performances of novel vertical device concepts based on Gr/WBS heterostructures will be discussed, in particular the ***Graphene/SiC Schottky diode with field-effect modulation of the barrier height*** for logic applications at

ultra-low power dissipation, and the ***Gr-base hot electron transistor on GaN*** for ultra-high frequency (THz) electronics.

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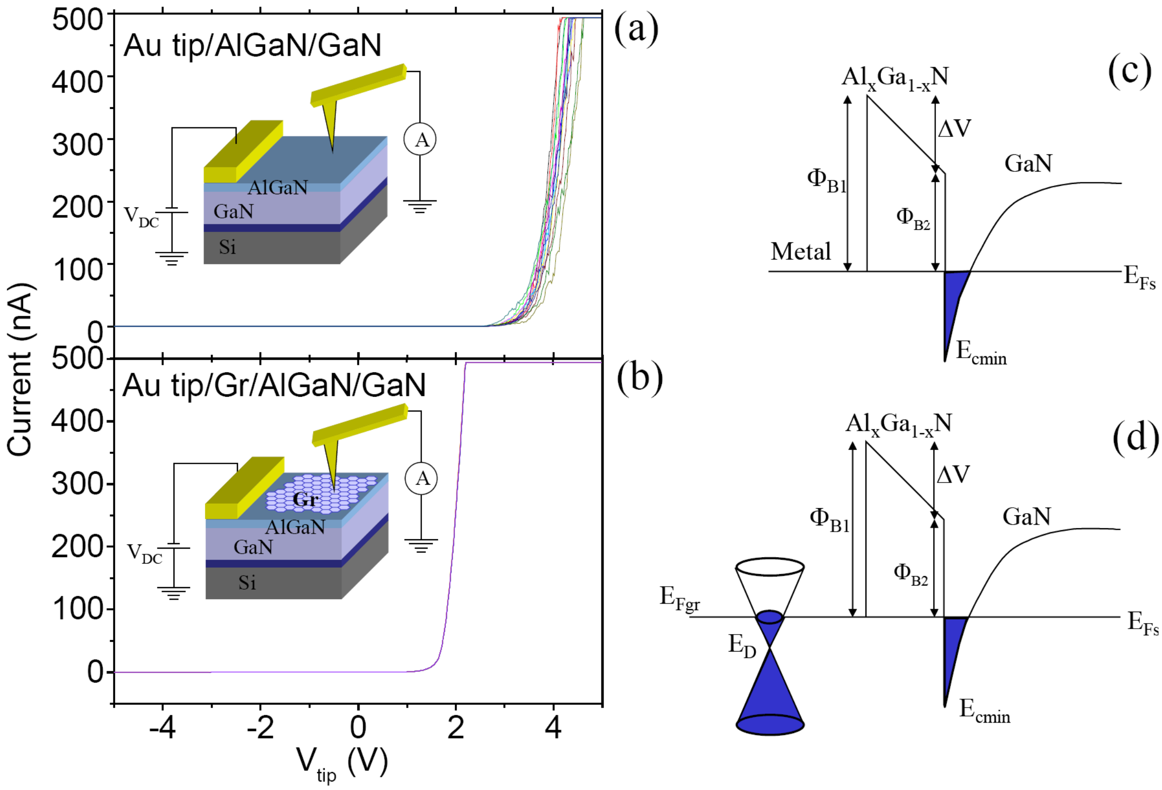

Fig. 1 Nanoscale resolution electrical characterization of vertical current transport at Gr/AlGaN/GaN heterostructures. Schematic representations of the experimental setup for local current–voltage measurements by conductive AFM (CAFM) are reported in the inserts of (a) and (b). Arrays of current-voltage curves collected using an AFM tip on several positions on AlGaN/GaN (reference sample) (a) and on Gr/AlGaN/GaN (b). This comparison demonstrates the high lateral uniformity of Gr Schottky contacts on AlGaN and the low Schottky barrier height (~0.4 eV). The conduction band diagrams of AlGaN/GaN (c) and Gr/AlGaN/GaN heterostructures (d) are also reported.