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Research paper

Evaluation of multilayer graphene for advanced interconnects

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ABSTRACT

In this work we are electrically characterizing multilayer graphene ribbons as potential Cu replacement towards future interconnect applications. We are comparing their performance with single-layer ribbons and we are reporting on sheet resistance, mobility and mean free path. We are additionally characterizing the contact properties for Pd contacts in top and edge configuration. Our results show high current carrying capacity for the multilayer ribbons and lower sheet resistance. Edge contacts to multilayer ribbons seem a promising approach for the decrease of the contact resistivity. Values of sheet resistance Rs ~280 Ω and contact resistivity Rc*W ~325 Ω·μm are measured for multilayer samples and edge contacts. Although the calculated ribbon mean free path is high for single-layer graphene (MFP_{SLG} ~60 nm), it is comparable with the MFP of Cu for the multilayer samples (MFP_{FLG} ~30 nm). Intercalation is a potential approach for improvement of the multilayer wire properties.

1. Introduction

The necessity of scaling in order to meet the requirements for the future technology nodes affects not only the active devices but also the chip interconnections. As interconnects face the continuous challenges of dimension shrinking, graphene has emerged as a promising material for the future wires. The current Cu interconnect technology faces a number of limitations while going to smaller nodes (higher wire resistivity, conductivity degradation, crosstalk, electromigration, thermally induced failures) [1,2]. Graphene with its high current carrying capacity, low capacitance, high electrical and thermal conductivity and immunity to electromigration can become a competitive solution, especially below 8 nm [3,4].

Additional improvement in performance is expected by utilizing multilayer graphene (MLG) for interconnects. Compared to single-layer graphene (SLG), MLG provides a larger number of conduction modes, a decrease in sheet resistance and smaller impact of the substrate and the surrounding [5–10]. Finally the possibility of MLG intercalation with suitable agents can further enhance performance with additional decrease of the sheet resistance and an increase in the number of available carriers [11–13]. It should be noted that the concept of MLG is different from the 3D graphite as in MLG the different layers are expected to interact as little as possible in order to individually maintain the superior SLG properties.

Among the biggest challenges for the use of the novel carbon materials is the fabrication of low-resistive metal contacts. The graphene quality, the type of substrate and the presence of impurities from processing are all parameters that influence the graphene/metal interface. The choice of metal is crucial as the metal/graphene interaction can be of different type and strength (weak physisorption, weak or strong chemisorption) leading to a different number of available conduction modes [6,14–18]. Finally the contact configuration plays a major role (top or side contacts). Top conduction happens through the graphene π-orbitals whereas edge conduction involves the graphene σ-orbitals. Edge contacting schemes have been demonstrated to result in lower contact resistance values in various works for SLG [19–23]. For MLG an edge contact can additionally provide access to all the graphene layers and can aid the reduction of the interlayer resistance [24].

In previous work [25] we have experimentally evaluated the performance of exfoliated MLG ribbons with top Pd contacts and compared with exfoliated and synthetic SLG ribbons. The results have shown that ribbons with <5 graphene layers (few-layer ribbons, FLG) result in the lowest contact and sheet resistance compared to MLG and SLG. Although graphene micromechanical exfoliation is the production method that yields material of the best quality, it is not suitable for upscaling towards large-area industrial applications. In addition, the exfoliated graphene multilayers are naturally coupled. Synthetic graphene is preferred towards upscaling, with CVD graphene

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(Chemical-Vapor-Deposition-grown graphene) being the most commonly used growth process [26].

In this work we are examining CVD FLG and MLG ribbons and we are comparing their performance with CVD SLG ribbons towards future interconnect applications. First we are evaluating experimentally the various ribbon properties (sheet resistance, mobility and the corresponding mean free path). Subsequently, special focus is given to the contact properties and the graphene/metal contact resistance is studied for the different ribbon types (SLG, FLG, MLG) and the two contact schemes (top contact, edge contact).

2. Materials and methods

Graphene of different number of layers was supplied from commercial vendors (SLG from *Graphenea*, FLG from *ACS Material*, MLG from *Graphene Platform*). FLG is nominally consisting of 5–8 layers and MLG is nominally consisting of 20–30 layers. All samples are transferred onto 90 nm SiO_2 substrates. Based on previous modeling work [4] this number of layers is considered sufficient for our studies. In the work of Pan et al. it was shown that, due to the increase of the wire capacitance in MLG, a continuous increase of the graphene layer number is not infinitely resulting in enhanced wire properties. There is rather a saturation point after which a drop in performance is observed compared to Cu interconnects.

Graphene ribbons are patterned using photolithography and shaped by oxygen plasma etch. Subsequently, the metal contacts are formed using photolithography followed by metal lift-off. The same fabrication process has been followed for all ribbon types (SLG, FLG and MLG, fabrication details are given in the Supplementary Information). In Fig. 1a an optical image of the starting blanket substrate is shown. In the inset of the image the shaped ribbon is shown, after the first photolithography step. In Fig. 1b an optical image of the final structure is shown. Top and edge contacts are both studied for SLG, FLG and MLG ribbons. The fabrication of edge contacts requires an additional oxygen plasma etching step after the second lithography step. After contact patterning the graphene at the contact area is etched away. The subsequent metallization results in the formation of edge contacts (Fig. S1). In Fig. 1c the various configurations under study are schematically represented, namely top and edge contacts on MLG (or FLG) and SLG graphene ribbons. Based upon literature reports and combined with our in-house experimental results [27], we used 50 nm thick Pd as the contact metal both for top and side contacts. Pd demonstrates low contact resistivity and in addition it is a fab-compatible metal.

The Transfer Length Method (TLM) [28,29] is used for the simultaneous extraction of the contact (Rc) and sheet resistance (Rs) as shown in Fig. 1d. Two-terminal devices of increasing channel length L are designed (cf. also Fig. 1b) and electrically characterized. The measured total resistance (R_{tot}) is plotted as a function of the graphene channel length, and after a linear fitting Rc is extracted from the intercept value, while Rs is extracted from the slope. Samples of 2×2 cm^2 are fabricated, containing a number of copies of every TLM structure. Ribbons of 5, 20 and 80 μm (width) are characterized. Channel lengths span from 2 μm up to 100 μm. Every TLM structure consists of 9 two-terminal devices. A systematic study is performed and statistics are collected, measuring up to 30 TLM structures per sample. Devices are measured in a back-gated configuration (measurement details are given in the Supplementary Information). All samples are annealed at 150 °C in N_2 for 1 h prior to the measurement in order to reduce the effect of doping from ambient conditions.

3. Results and discussion

The Raman signatures of the different samples are shown in Fig. 2. The I_{2D}/I_G ratio and the shape of the 2D peak are different among samples with different numbers of graphene layers. SLG is typically characterized by a sharp 2D peak and an I_{2D}/I_G ratio higher than 1. $I_{2D}/I_G < 1$ indicates the presence of more than one graphene layer. Additionally with an increase in the layer number the 2D peak is broadened.

Typical Id-Vg curves obtained for the different ribbon types (SLG, FLG and MLG) are shown in Fig. 3. The curves are plotted for three different channel lengths (5, 25 and 50 μm) and a ribbon width of 20 μm. SLG and FLG data are aligned around the neutrality point, where $Vg - Vnp = 0$ V.

With the back gate (Vg) sweep, the typical monolayer graphene response is observed for the SLG samples (black, dashes). The presence of only few carriers around the neutrality point results in very low current. As the gate voltage increases towards higher positive or negative values a fast increase of current is observed as more carriers are available for conduction. This fast increase is a signature behavior for graphene originating from the particular graphene conical band structure. This response is even more enhanced for samples close to ideal quality (e.g. for exfoliated material, suspended samples uncoupled from any substrate, measured under vacuum conditions and low T) where record mobility values up to 200.000 $cm^2/V \cdot s$ have been measured [30]. The addition of more graphene layers changes the graphene band structure and for the FLG samples (red, solid) less current modulation is observed.

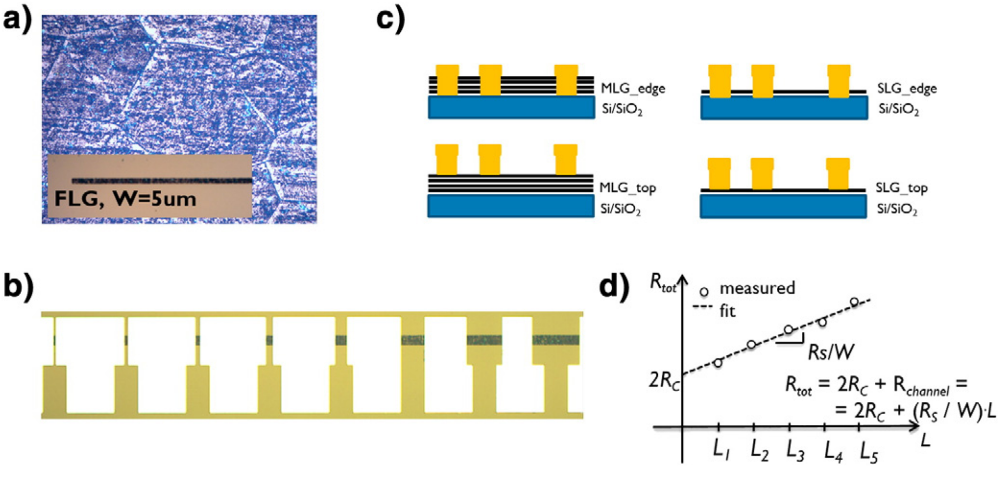

Fig. 1. (a) optical image of the starting substrate of large area MLG graphene. Inset: optical image of one of the patterned graphene ribbons obtained after the first lithography shaping step. (b) Optical image of the final graphene TLM structure (top view) and (c) schematic representation (side view) of the different samples examined. Top and edge contacts are studied on MLG (or FLG) and SLG graphene ribbons. (d) Schematic representation of the TLM and the Rc and Rs extraction model.