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Current injection from metal to MoS_2 probed at nanoscale by conductive atomic force microscopy

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ABSTRACT

Contacts with MoS_2 are currently the object of many investigations, since current injection through metal/MoS_2 interfaces represents one of the limiting factors to the performance of MoS_2 thin film transistors. In this paper, we employed conductive atomic force microscopy (CAFM) to investigate the current injection mechanisms from a nanometric contact (a Pt coated tip) to the surface of MoS_2 thin films exfoliated on SiO_2. The analysis of local current–voltage (I–V) characteristics on a large array of tip positions provided high spatial resolution information on the lateral homogeneity of the tip/MoS_2 Schottky barrier Φ_B and of the ideality factor n. From the histograms of the measured Φ_B and n values, an average Schottky barrier height of 297 meV with standard deviation of 22 meV and an average ideality factor of 1.65 with a standard deviation is 0.15 have been estimated. The implications of these lateral variations of Φ_B and n in MoS_2 nano-Schottky diodes on the electrical properties of macroscopic contacts to MoS_2 have been discussed also in relation with recent literature results.

1. Introduction

The isolation of graphene, the single atomic layer of sp^2 carbon, by exfoliation of graphite represented the first experimental demonstration that two dimensional (2D) materials can be stable under ambient conditions after separation from the bulk crystal [1]. This opened also the way to the investigation of an entire class of layered materials occurring in nature, which are composed by the vertical stacking of 2D sheets bond by van der Waals interaction [2]. In particular, transition metal dichalchogenides (TMD), whose generalized formula is MX_2, where M is a transition metal of groups 4–10 and X is a chalcogen (S, Se,...), attracted significant interest in the last years [3]. Some of them (in particular MoS_2) are naturally abundant in nature and very stable after exfoliation. Furthermore, MoS_2, $MoSe_2$, WS_2, WSe_2 have been shown to be semiconductors with sizable bandgaps [3]. Interestingly, for few layers samples the bandgap has been found to be layer-number dependent and a transition from indirect to direct bandgap is observed from bilayer to monolayer. The semiconducting properties make TMD very attractive for electronics and optoelectronics even with respect to graphene, for which some applications are hindered by the lack of a bandgap in the electronic energy spectrum.

As an example, MoS_2 has currently being considered as a candidate for next generation post-Si CMOS technology. Due to the intrinsic stability of the material, MoS_2 thin film transistors guarantee the scalability of the channel thickness down to the ultimate single layer limit that cannot be achieved by Silicon on Insulator (SOI) technology. Very promising performances, such on/off current ratios $>10^7$ and nearly ideal subthreshold swing (≈ 70 mV/decade) have been already demonstrated for top gated monolayer MoS_2 transistors with high-k gate dielectrics [4]. Recently, multilayer MoS_2 (with thickness up to 50 nm) have been also evaluated for MOSFETs applications and several advantages have been identified with respect to single layer devices, such as higher drive current, due to the three times higher density of states in multilayer than in single layer [5], and better current saturation behavior in the output characteristics [5,6].

In spite of these great promises, processing for MoS_2 devices is still in its infancy and several issues, including the scalable growth of MoS_2 films with controlled thickness [7], the formation of low resistance Ohmic contacts [6], optimal gate dielectrics, surface passivation and doping are currently object of investigation to fully exploit the potentialities of this material.

In particular, source/drain contact resistances have been currently identified as limiting factors for MoS_2 transistors performances, leading to a severe underestimation of the field effect mobility and to a general degradation of device characteristics [6]. MoS_2 thin films obtained by exfoliation from bulk molybdenite are

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typically unintentionally n-type doped [8]. Since methods for selective-area doping of MoS_2 are still lacking, source/drain contacts are typically deposited directly on the unintentionally doped MoS_2 surface, resulting in the formation of a Schottky barrier. Experiments have shown that Schottky barrier height values for most of elementary metals can range from ~25 to ~300 meV, going from low work-function metals (such as Sc) to high work-function metals (such as Pt) [6]. Such a behavior has commonly been ascribed to a pinning of the Fermi level of metals in the upper part of MoS_2 bandgap. However, the origin of this effect is still matter of debate. Recent experimental investigations by scanning tunneling microscopy (STM) or spectroscopy (STS) revealed a high degree of electrical inhomogeneity on the surface of as-exfoliated MoS_2 [9]. In particular, a high density of nanometric sulfur vacancies clusters with metallic behavior has been observed, which can represent preferential paths for electron injection from a deposited metal contact.

These literature works indicate that nanoscale resolution electrical characterizations can represent a powerful method to understand the electrical behavior of metal/MoS_2 contacts. AFM-based electrical characterization techniques have been extensively applied in the last years to locally investigate the potential distribution [10], capacitance [11], conductivity [12] and electron mean free path [13,14] of graphene, as well as the uniformity of the Schottky barrier height at the junction between graphene and semiconductors [15,16]. To date, these scanning probe methods have been applied lo a lesser extent to TMD. In this paper, we employed conductive atomic force microscopy (CAFM) to investigate the current injection mechanism from a nanoscale metal contact, i.e. the AFM tip, to the surface of MoS_2 thin films exfoliated on a SiO_2 substrate. Local current–voltage characteristics measured by CAFM provided high spatial resolution information on the lateral homogeneity of the metal/MoS_2 Schottky barrier.

2. Experimental

MoS_2 samples have been obtained by mechanical exfoliation of bulk molybdenite crystals purchased by SPI. The exfoliation technique was based on the use of a thermal release tape with typical release temperature of 130 °C and thermo-compression printing [17]. After printing on the SiO_2(300 nm)/Si target substrate, the sample surface was carefully cleaned by using solvents in an ultrasonic bath. MoS_2 flakes of different lateral size and variable thickness (from single layer to multilayers) were obtained on SiO_2 by this approach. Preliminary inspection of MoS_2 flakes was performed by optical microscopy (OM). The variable flakes thickness produces a variable contrast in OM images, due to the light

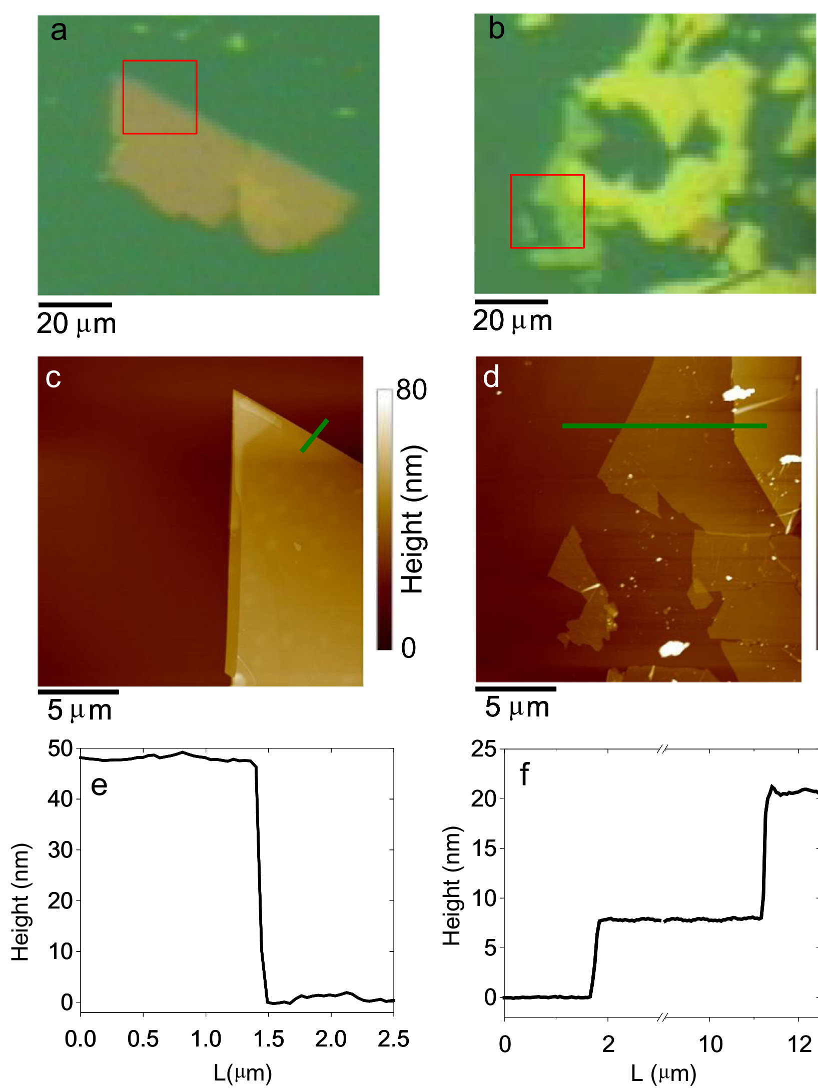

Fig. 1. (a,b) Representative OM images on MoS_2 flakes of different sizes and thickness uniformity. (c) (d) AFM images of selected areas in these samples and (e,f) corresponding height line-scans.

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