Report of Short Term Mobility (STM) program 2017 performed by Giuseppe Greco (CNR-IMM)

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Title of the program : Gr and TMDs based heterostructures for next generation transistors

In recent years, significant progress has been made in the application of two-dimensional (2D) layered materials having individual planes with an atomic-scale thickness. 2D layered materials such as transition metal dichalcogenides (TMDs)[1] with no out-of-plane bonds offer interesting opportunities for integration with bulk semiconductors such as Si, SiC and GaN. Integration of diverse bulk semiconductors is limited by the need for lattice matching and extended defect control. With no constraints of lattice matching, 2D materials can be integrated with bulk semiconductors to create vertical and lateral heterostructures. More recently, researchers have started exploring such 2D/3D heterojunctions for device applications. MoS_2/Si heterojunctions have been investigated for device applications such as photodetectors[2,3] and solar cells[4]. Researchers have also studied MoS_2/SiC[5] and MoS_2/GaN[6,7,8,9] heterojunctions for a wide range of device applications as low power logic devices with steep subthreshold slope[10]. A suitable application for MoS_2/GaN heterostructures can be found in Esaki interband tunnel diode[11]. In fact, a very low value of conduction band offset ΔE_C = 0.2 eV , and a very small value of built in potential (V_{bi}=1.5 eV) in the space charge region can be observed in MoS_2/GaN heterostructures[12].

Moreover, integration of 2D material as MoS_2 with Wide Band Gap (WBG) materials, as GaN are particularly interesting due to the complimentary properties of these material systems. WBG materials have high breakdown fields suitable for high power/voltage device operation. Instead, 2D materials can offer excellent current spreading properties due to high mobility even when they are atomically thin. Then, they can use as conductive base layers in vertical 2D/3D heterojunctions-based vertical heterojunctions bipolar transistors or unipolar hot electron transistors (HET) for high frequency applications[13]. Then, Gr or TMDs materials have been identified as suitable material to be implemented as base electrode in HET devices. These devices typically show high ON/OFF current ratios, not reachable by conventional lateral GFETs, that make them suitable for logic and switching applications, able to operate at ultra-high frequencies up to THz.

Then, during the Short Term Mobility (STM) program, several Gr and TMDs heterostructures were fabricated at Izmir Institute of Technology (IZTECH). The substrates for TMDs and Gr have been provided from IMM. In particular, two 6 inches wafers of Al_2O_3 and HfO_2 deposited on n-type Si substrate, by Atomic Layer Deposition (ALD) have been provided for deposition of TMDs or TMDs/Gr. In addition, undoped GaN and an n-type doped GaN layer, both grown on sapphire substrate, have been provided for deposition of TMDs material. Finally a small sample of n-type GaN grown on bulk GaN have been provided for TMDs deposition. In Table I it is reported a list of the substrates provided by the IMM for the TMDs or TMDs/Gr deposition. The morphology of the provided samples have been also reported in the table as RMS.

Sample	Substrate	RMS (nm)
T-Al_2O_3 - 20nm	Al_2O_3/n-Si	0.17
T-HfO_2 - 9nm	HfO_2/n-Si	0.18
# AX2989 - 1A	u.i.d. GaN/sapphire	1.0
# AX2586	n-GaN/sapphire	1.5
FSLEDQE51N _ 06-483	n-GaN/bulk-GaN	4.4

Table I: List of substrates provided by the IMM for the TMDs or TMDs/Gr deposition

Then, MoS_2 flakes have been prepared by the liquid exfoliation method [14]. Few-layer MoS_2 was prepared by mixing in 2–3ml solutions of the MoS_2 powder dissolved in ethanol/water (0.5mg/ml-2 mg/ml). The MoS_2 suspensions were sonicated for 120 minutes at a power of 225 W in a water-cooled bath. After the sonication, the final dispersions were centrifuged at 12000 rpm for 30min and the top 3/4 of the supernatant was collected. The obtained MoS_2 samples were dissolved in ethanol/water, and dropped onto some part of the provided substrate.

In order to get information on the successful of the MoS_2 heterostructures fabrication, a Raman spectroscopy analysis have been carried out. In Fig. 2a and Fig.2b, a schematic and a photograph of the experimental setup used for Raman measurements are shown.

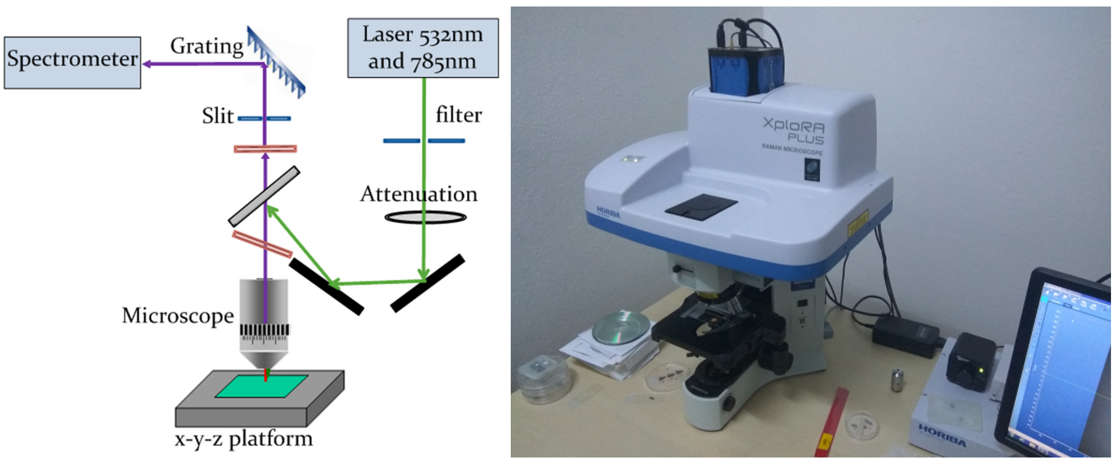
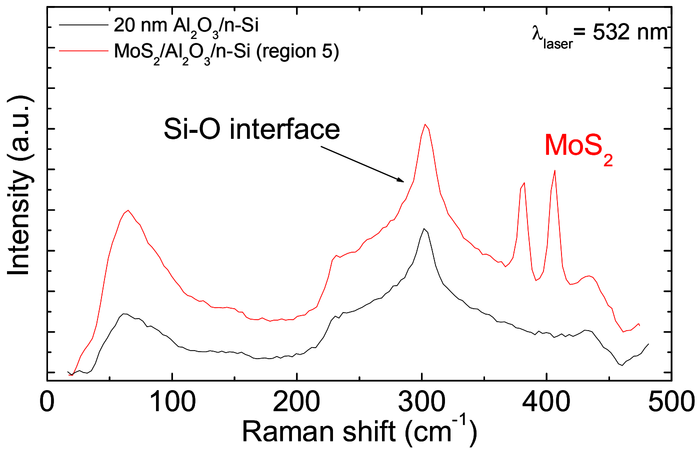


Fig.2: Schematic of the experimental setup used for Raman spectra analysis (a), and a photograph of Raman facilities present at IZTECH (b).

As first, the Raman measurements of the MoS_2/Al_2O_3 and MoS_2/HfO_2 heterostructures have been performed. In Fig. 3a, the Raman spectra of the Al_2O_3/n-Si substrate and of the MoS_2/Al_2O_3/n-Si heterostructures have been reported. In the Al_2O_3/n-Si reference sample a peak related to the Si-O bond can be observed. This peak is related to the Si-O bonds presented at Al_2O_3 - Si interface. Instead, in the MoS_2/Al_2O_3 sample, the peak related to the MoS_2 flakes appears. Moreover, because of the small thickness of the MoS_2 flakes, the peak related to the Al_2O_3 - Si interface is still visible. In Fig. 3b, the region of the MoS_2/Al_2O_3/n-Si, where the Raman measurements have been performed is shown. To exactly estimate the number of MoS_2 layer, AFM measurements will be performed at CNR-IMM of Catania.



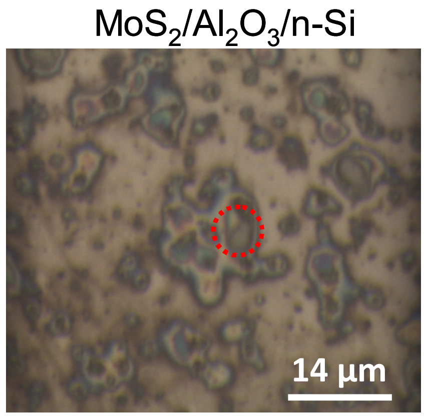
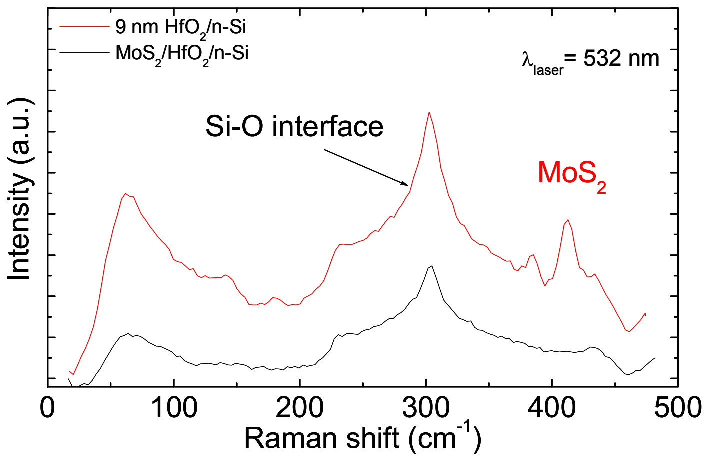


Fig.3: Raman spectra of the Al_2O_3/n-Si substrate and of the MoS_2/Al_2O_3/n-Si heterostructures (a) and an optical image of the MoS_2/Al_2O_3/n-Si investigated region (b).

A similar analysis have been performed in the samples of HfO_2/n-Si and MoS_2/HfO_2/n-Si. In Fig. 4a and Fig. 4b the Raman measurements and an optical image of the MoS_2/HfO_2/n-Si investigated region can be observed. Also in this case, the peak related to the Si-O bonds present at the interface can be observed in both samples. Also in this case the sample with the MoS_2 shows the characteristic peak, which demonstrated the successful of the MoS_2 deposition.



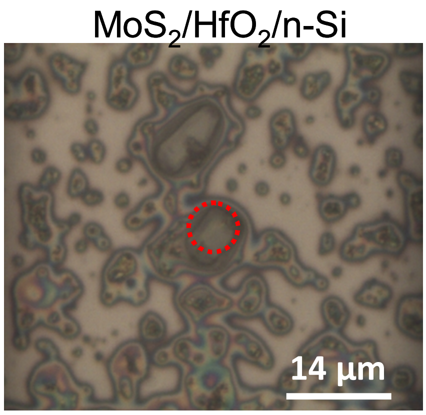


Fig.4: Raman spectra of the HfO_2/n-Si substrate and of the MoS_2/HfO_2/n-Si heterostructures (a) and an optical image of the MoS_2/HfO_2/n-Si investigated region (b)

Very interesting was the structural investigation performed by Raman measurement, on GaN samples grown on sapphire (see Fig. 5). In particular, the Raman shift obtained in u.i.d GaN (black line) and n-type (1×10^{17} cm^{-3}) GaN (red line) have been compared. From Raman spectra, the characteristic peaks of GaN can be easily observed. Moreover, from a comparison of the spectra acquired in undoped and n-type doped sample (see Fig. 6a and Fig. 6b) a shift of the peak E_2 and

A_1 can be observed. Moreover a vanishing of the A_1 peak is clear evident (Fig. 5). Both effects indicates an increasing of the Si doping concentration in GaN[15].

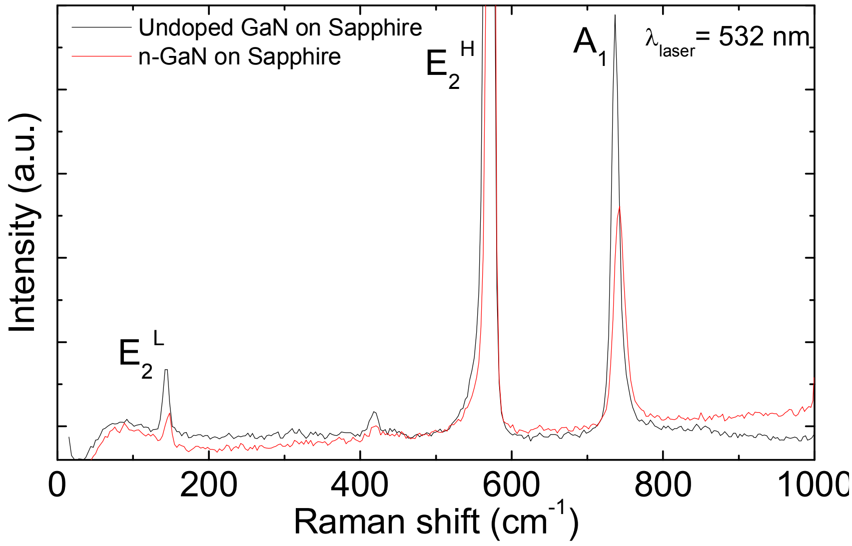


Fig. 5: Raman measurement of the undoped and n-doped GaN layer grown on Sapphire.

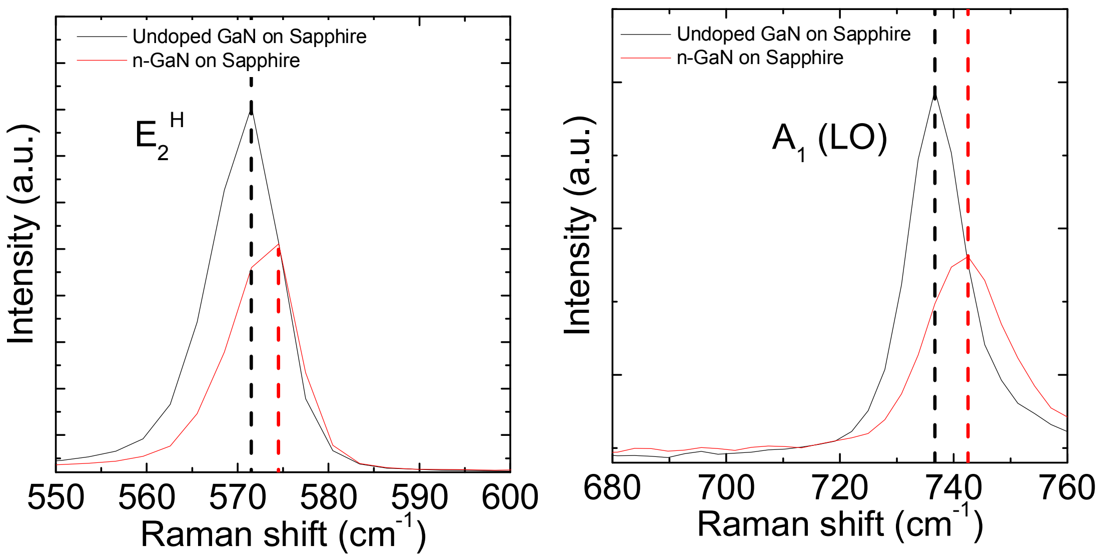


Fig. 6: An enlarged view of the Raman shift observed in E_2^H (a) and A1 (LO) (b) peaks.

After an investigation of the GaN samples by Raman measurements, the GaN substrates have been investigated also after MoS_2 deposition (see Fig. 7 and Fig. 8). Also in this case the spectra with

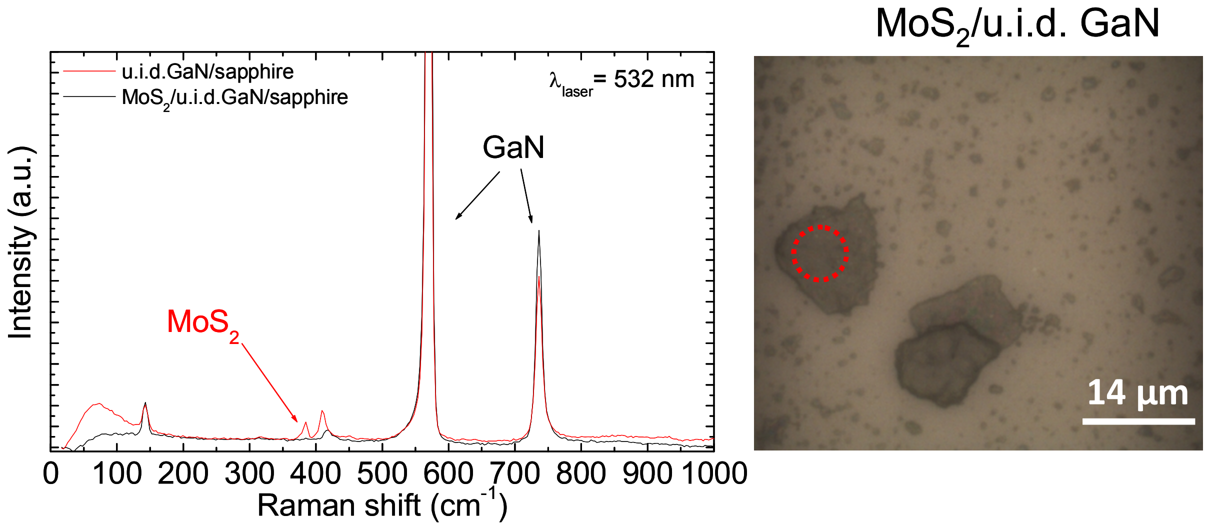


Fig.7: Raman spectra of the u.i.d. GaN and of the MoS_2/u.id. GaN heterostructures grown on sapphire substrate (a) and an optical image of the MoS_2/u.i.d. GaN investigated region (b)

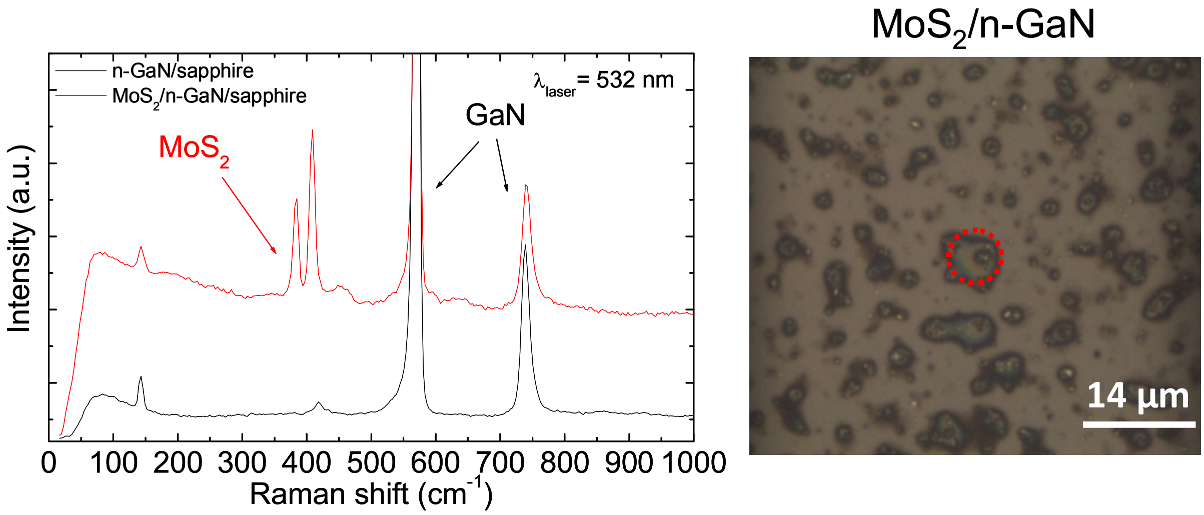
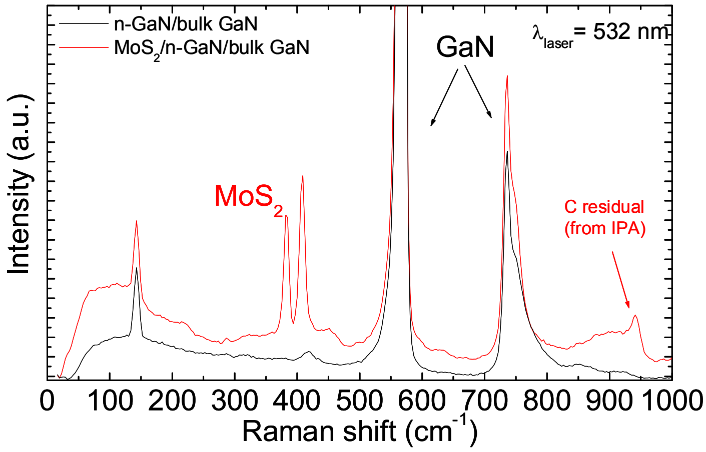


Fig.8: Raman spectra of the n-GaN and of the MoS_2/n-GaN heterostructures grown on sapphire substrate (a) and an optical image of the MoS_2/n-GaN investigated region (b).

Finally, Raman measurements have been carried out also in the sample of MoS_2/n-GaN grown on bulk GaN. In Fig. 9 the Raman spectra of the reference and of the sample with MoS_2 is shown. Also in this case the peaks related to the MoS_2 are well evident. Moreover, in this case a peak around 950 cm^{-1} can be observed. This peak can be correlated with the presence of C from IPA solution.



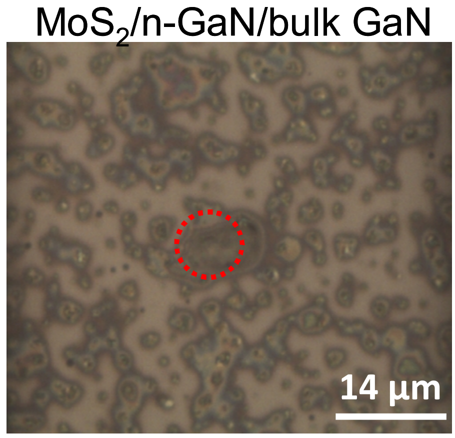


Fig.9: Raman spectra of the n-GaN/bulk-GaN and of the MoS_2/n-GaN/bulk-GaN heterostructures (a) and an optical image of the MoS_2/n-GaN/bulk-GaN investigated region (b).

In conclusion, during the visiting period, MoS_2 layer have been successfully deposited on several substrates. A structural analysis of the fabricated heterostructures have been performed by Raman measurements. Then, in order to electrical investigate the fabricated heterostructures, Conductive Atomic Force Microscopy (CAFM) will be performed in Catania in the same regions investigated by Raman analysis.

DATA
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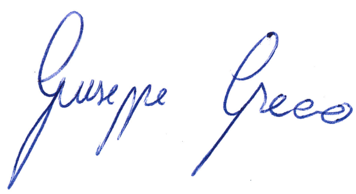

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