Patterning metal contacts on monolayer MoS_2 with vanishing Schottky barriers using thermal nanolithography

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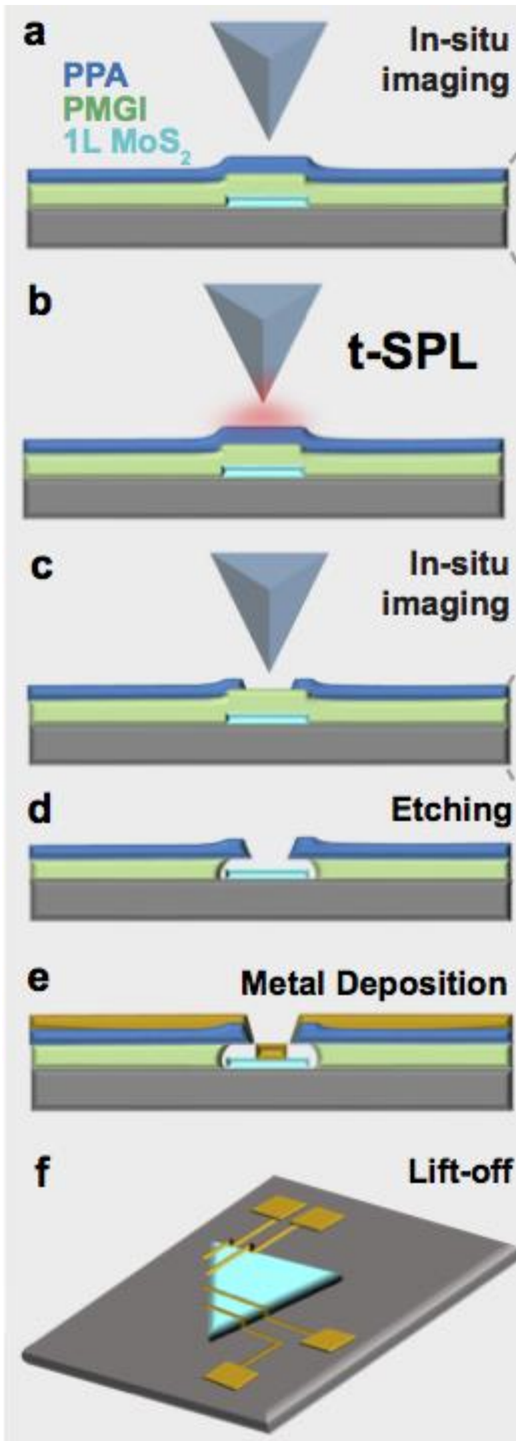
Among various novel materials, two-dimensional molybdenum disulfide (MoS_2) is of particular interest due to its large band gap, low dielectric constant, and heavy carrier effective mass. Currently, a key issue in creating high performing field-effect transistors (FETs) based on MoS_2 and other transition metal dichalcogenides (TMDC) films is the poor quality of the metal contacts fabricated on these atomic layers, which gives rise to non-ohmic contacts, high Schottky barriers and large contact resistances. Several approaches have been proposed to solve these problems, including trying different metallic alloys and doping, using a metallic phase of MoS_2 or a h-BN layer as interface between the metal contact and the semiconducting MoS_2 layer, and exploiting graphene as contact. However, all these strategies are either non-scalable or have not yet been fully developed. They also all rely on conventional fabrication methods, typically EBL, for metal contact patterning. EBL is currently the most widespread and reliable nanomanufacturing method for metal electrode patterning when nanoscale dimensions are required. The technique requires ultra-high vacuum (UHV) and does not allow in situ imaging. Its scalability is also limited by the costs and complexity of a multi-beam systems. Furthermore, primary and secondary electrons in EBL, as well as ultraviolet (UV) exposure in optical lithography, can damage 2D materials, from graphene to TMDC films.

Here, we report a strategy to fabricate metal contacts on 2D materials with high reproducibility [1]. Our approach is based on a double polymer stack chemical etching/lift off process combined with thermal scanning probe lithography (t-SPL) [2]. Using a commercial system based on t-SPL, top-gated and back-gated monolayer (a single atomic layer, 1L) MoS_2 FETs are fabricated with different metals as direct contacts on the MoS_2. The approach does not require vacuum, allows for in situ simultaneous patterning and imaging of a monolayer of MoS_2, can achieve sub-10 nm resolution, gives rise to no resist contamination, and completely eliminates damage from either electrons or photons. As a result, the t-SPL fabricated FETs exhibit on/off ratios up to 10^{10}, Schottky barrier heights (SBH) close to 0 mV, and sub threshold swings as low as 64 mV/dec without using negative capacitors or hetero-stacks, outperforming EBL results in literature. Applications to other TMDC are also reported. The technique, which currently runs with a single scanning probe, has a throughput of 10^5 μm^2/h per single probe, similar to EBL and can readily be implemented in a cost-effective manner to multiple probes to increase throughput.

[1] "Patterning metal contacts on monolayer MoS_2 with vanishing Schottky barriers using thermal nanolithography", *Nature Electronics*, 2, 17–25 (2019) https://doi.org/10.1038/s41928-018-0191-0

[2] "Advanced Scanning Probe Lithography", *Nature Nanotechnology*, 9, 577 (2014) DOI: 10.1038/NNANO.2014.157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In-situ
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1L MoS2
b
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Metal Deposition
f
Lift-off