**Effects of spatially-varying helium ion beam irradiation on monolayer MoS2 field effect transistors**

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**250 word abstract, 3500 word paper, 200 words per figure, 13 words per table**

One morning, when Gregor Samsa woke from troubled dreams, he found himself transformed in his bed into a horrible vermin. He lay on his armour-like back, and if he lifted his head a little he could see his brown belly, slightly domed and divided by arches into stiff sections. The bedding was hardly able to cover it and seemed ready to slide off any moment. His many legs, pitifully thin compared with the size of the rest of him, waved about helplessly as he looked. "What's happened to me?" he thought. It wasn't a dream. His room, a proper human room although a little too small, lay peacefully between its four familiar walls. A collection of textile samples lay spread out on the table - Samsa was a travelling salesman - and above it there hung a picture that he had recently cut out of an illustrated magazine and housed in a nice, gilded frame. It showed a lady fitted out with a fur hat and fur boa who sat upright, raising a heavy fur muff that covered the whole of her lower arm towards the viewer. Gregor then turned to look out the window at the dull weather. Drops of rain could be heard hitting the pane, which made him feel quite sad. "How about if I sleep a little bit longer and forget all this nonsense", he thought, but that was something he was unable to do because he was used to sleeping on his right, and in

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**Layered two-dimensional (2D) semiconductors have emerged in recent years as promising candidates for low-power miniaturized electronics. In particular, transition metal dichalcogenides (TMDs) such as MoS2 and WSe2 have demonstrated impressive ON/OFF ratios (~ 107) while maintaining relatively high field effect mobilities (1 – 480 cm2 V-1 s-1) in two-terminal devices1–5. With chemical vapor deposition (CVD) techniques now allowing centimeter-scale fabrication of well-performing monolayer TMD films {REF}, it becomes crucial to understand the role of defects such as chalcogen vacancies and grain boundaries on the electrical transport properties of these materials. Moreover, the introduction of defects into TMD field effect transistors (FETs), may serve to improve charge transport if done controllably {REF}.**

**Recently, light ion beam irradiation (He+, Ne+, Ar+) has opened the field to exploring the effects of modifying TMD devices on the nanometer scale. The localized formation of defects by ion irradiation has been shown to induce unusual electronic properties in monolayer TMDs, such as a metallic transitions in MoS2, WSe2 and WS26,7, …**

**Monolayer MoS2 samples were grown onto 285 nm SiO2/Si substrates by a CVD method described in previous work {REF}. The resulting flakes were usually triangular in shape with a good concentration of isolated samples present on the substrate due to this growth method. A representative scanning electron micrograph (Zeiss Supra) is shown in Fig. 1(a). Electron beam lithography was then used to contact isolated flakes with 5 nm Ti/35 nm Au electrodes. All FET channels fabricated for this work had a width of 5 µm. The electrodes were deposited in a geometry perpendicular to the edge of the MoS2 triangles, as to avoid any transport discrepancies resulting from crystal orientation {REF}. Some channels were fabricated on the same MoS2 flake. An optical micrograph of a typical contacted device is presented in Fig. 1(b). The metal film was lifted off in acetone overnight, and the devices were not annealed prior to electrical testing. Characterization was carried out in the vacuum chamber of a customized scanning electron microscope (Zeiss EVO), after devices were pumped at a pressure of ~ 10-5 mbar for 12 hours. Imina miBot probes were used to contact the device to a dual channel sourcemeter (Agilent BX). The FETs were back-gated through the highly p-doped Si substrate attached to copper tape. Raman and photoluminescence spectroscopy was carried out to determine the quality and layer number of the tested samples. The spectra were acquire at x using a WiTEC x system at 532 nm with grating blabla. Typical spectra of the monolayer flakes are presented in Fig. 1(c)-(d). The separation of the E and A modes is in good agreement for literature numbers for single layer MoS2 {REF}. The PL emission is strongly centred at 1.85 eV, indicating the direct-recombination peak of monolayer MoS2 {REF}.**

**Helium ion irradiation was carried out in a Zeiss Nanofab microscope at a beam energy of 30 keV and He gas pressure of 2 × 10-6 mTorr. The average beam current (aperture 20 µm) was 37.47 ± 0.38 pA, with the minimum probe size evaluated at 7 nm (see supplementary material in (ref Fox) for details on evaluation of probe size. The He ion dose delivered to each sample was 1017 ions cm-2, with a probe step size of 1 nm and dwell time of 4.3 µs. The irradiation patterns were draw on the Zeiss ZEN software, with the width of the irradiated area, W, calculated from…**

**Figure 2(a) shows a sketch of the experimental geometry. The as-made MoS2 FETs were placed in the helium ion microscope after initial electrical testing and were all irradiated within the same day without leaving vacuum, with the stage tilt set at 0º. Ion exposure to the devices was minimal before commencing irradiation (limited to the quick image grab dose which is ~ 5 orders of magnitude less than the working dose). A focused probe was obtained away from the MoS­­2 devices to reduce unnecessary exposure. A typical SEM micrograph of an irradiated device is presented in Fig. 2(b). The marked distances and denote the width of the irradiated region and length of the FET channel respectively. L was always 5 µm in this work, while was varied in order to obtain a damage-to-channel ratio, . Following the patterning and electrical testing, the devices were analyzed in the SEM. As the chosen dose will inevitably lead to damage extension past the designed region, the true irradiated area of the channel was measured and divided by the true area of the channel. This ensures a highly accurate ratio of the beam-damaged MoS­­2 material. Thus, when referring to the irradiation ratio in the rest of the manuscript, ,we will mean this true ratio obtained post-experiment.**

**The typical effect of irradiating the MoS2 sample at the dose of 1017 ions cm-2 is shown in Figure 2(c). Just as in our previous work7, this high dose causes a notably higher electrical conduction to emerge in the monolayer MoS­2, with output current (green) nearly doubling for the same drain-source bias when compared to the as-made device (blue). The post-irradiation transfer characteristics (green), in turn, reveal a much-reduced response to changes in the gate bias. The nominally semiconducting FET channel cannot now be effectively turned off in the tested bias range, with significant current still present at . This is in stark contrast to the n-type device behavior noted for the MoS­2 channel pre-irradiation (blue). The sharp rise in the subthreshold swing and the huge shift of the threshold voltage to negative gate biases experienced by the device may have several origins. The presence of the metallic 1T-MoS2 phase results in no gate tunability8–10, while the present device retains a small ON-OFF ratio of ~ 10. Highly sulfur vacancy-rich MoS2 samples have been shown to also possess a decreased sensitivity to gate voltage11,12healingSVs. If SVs are being created by the ion beam and are acting as donors to the FET channel, the threshold voltage will inevitably shift to higher negative biases.**

**See supplementary material for information on…**

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