Radiation tolerance of two-dimensional material-based devices for space applications

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Characteristic for devices based on two-dimensional materials are their low size, weight and power requirements. This makes them advantageous for use in space instrumentation, including photovoltaics, batteries, electronics, sensors and light sources for long-distance quantum communication. Here we present a comprehensive study on combined radiation effects in Earth’s atmosphere on various devices based on these nanomaterials. Using theoretical modeling packages, we estimate relevant radiation levels and then expose field-effect transistors, single-photon sources and monolayers as building blocks for future electronics to γ-rays, protons and electrons. The devices show negligible change in performance after the irradiation, suggesting robust suitability for space use. Under excessive γ-radiation, however, monolayer WS2 shows decreased defect densities, identified by an increase in photoluminescence, carrier lifetime and a change in doping ratio proportional to the photon flux. The underlying mechanism is traced back to radiation-induced defect healing, wherein dissociated oxygen passivates sulfur vacancies.
In the near future, quantum tunneling will set a hard limit to further miniaturization of silicon-based electronics. Research on alternative materials, however, demonstrated fabrication beyond this limit\(^1\). Of particular interest are monolayered two-dimensional (2D) materials such as graphene\(^2\) and transition metal dichalcogenides (TMDs) of the form of MX\(_2\) (M = Mo, W and X = S, Se). Record electron mobility in 2D materials has enabled multiple technology demonstrations of atomically thin field-effect transistors (FETs)\(^3\). Furthermore, due to their semiconducting bandstructure, TMDs have applications in optoelectronics and photonics\(^4\). Their intrinsically low size, weight, and power requirements and chemical stability make 2D material-based devices a promising candidate for space instrumentation. Beyond integrated electronics, 2D materials in space technology can be utilized for solar cells\(^5\), batteries\(^6\), sensors as well as non-classical light sources for long-distance quantum communication\(^7\). The quantum emission from point defects in 2D materials has desirable properties for single-photon sources, as they can be easily integrated with photonic networks, have an intrinsic out-coupling efficiency of unity, and offer long-term stable, high-luminosity single-phots at room temperature (RT)\(^8\,9\). An ideal single-photon source can enhance the data communication rates of satellite-based quantum key distribution\(^10\).

While 2D materials offer great opportunities for space missions, their current low technological readiness level (TRL) restricts deployment (current state-of-the-art is TRL 3–4). In addition to further device development, 2D materials need to be certified for the harsh conditions of space. Space qualification studies usually consist of vacuum and thermal cycling, vibration, and shock tests as well as exposure to radiation\(^11\). Vibration or shock will not pose a threat for nanomaterials and vacuum and thermal cycling is routinely done in experiments\(^12\,13\). Of particular interest, however, is the effect of radiation on 2D materials. While radiation effects on the electrical properties of graphene have been studied extensively\(^14\), less is known about these effects on TMDs and other 2D materials\(^15\–19\). In particular, no study investigates the effect of radiation on optical characteristics of 2D materials. Moreover, there exists no comprehensive study on the effects of combined radiation types on properties of various devices in the context of space certification. The damage caused by high-energy particles and \(\gamma\)-rays is of major concern for all spacecraft, especially as weight restrictions limit shielding options. While testing directly in a space environment as planned for graphene is possible\(^20\), a more practical way is to replicate space environments on Earth.

As already mentioned, single-photon sources based e.g. on defects in hexagonal boron nitride (hBN) and FETs based on monolayers are useful for space applications. These devices are influenced by their electrical and/or optical properties (quantum emitters in hBN are dependent on the piezoelectric environment of hBN\(^21\)). It is possible that low-energy radiation on the order of the bandgap (-1–10 eV) could change the charge state of defects, causing them to enter a dark state, usually for a finite time. High-energy radiation, on the other hand, could create new defects in the crystal lattice. If close to the quantum emitter, the new defects could either change the charge state permanently or create a second independent emitter nearby. In any of these scenarios, the single-photon source would become unusable. With respect to the FETs, the radiation could change the carrier density, which alters their performance.

Here we present a comprehensive study on the effects of radiation in the atmosphere on various devices based on 2D materials. We start with modeling radiation levels in the thermosphere using the SPace ENVironment Information System (SPENVIS), software provided by the European Space Agency\(^22\). With the knowledge from the simulations, we expose our devices to the most common radiation types in orbit: gamma-rays as well as energetic protons and electrons. We look at isolated effects and combined effects by exposing devices to all three types of radiation. For each test, we fully characterize all devices back to back, shortly before and after the exposure. At radiation levels common for satellite altitudes up to geostationary orbit, no changes in the characteristics of the 2D materials are observed. However, under excessive \(\gamma\)-irradiation, WS\(_2\) monolayers exhibit significant change in its optical emission. By studying the effects of oxygen plasma and \(\gamma\)-irradiation in different atmospheres, the mechanism is traced back to oxygen-related vacancy healing. Additional density functional theory (DFT) calculations show that charge trapping states disappear after the healing, thus explaining the change in optical emission.

**Results**

**Radiation levels in orbit.** The Earth is protected from solar wind and cosmic particles by its magnetic field. As a result, high-energy protons and electrons are trapped on trajectories oscillating between both magnetic poles in the so-called Van Allen belts. While essential for life on Earth, the trapped particle belts pose great threat to any spacecraft orbiting through these particle belts. Near the magnetic poles, the inner belt can extend down to altitudes of 200 km. Owing to misalignment of the magnetic dipole and rotation axis of the Earth, this appears as the South Atlantic Anomaly (SAA; see Fig. 1a, b). Because of this inhomogeneity, the total radiation dosage is strongly dependent on the orbital inclination. Thus we calculated the particle spectra for different spacecraft trajectories with inclinations of 20° (here defined as equatorial orbit), 51.6° (orbit of the International Space Station (ISS)), and 98° (here defined as polar orbit) for 500 km altitude and average over the full orbit. In general, the energy spectrum for protons in low Earth orbit (LEO) ranges from 100 keV to 400 MeV, while for electrons it ranges from 40 keV to 7 MeV. Low-energy particles are typically absorbed by the walls of the spacecraft, which acts as a non-ideal high-pass filter. High-energy ions, however, lose energy during their interaction with the shielding material and thus the lower ends of the spectra are always finite unless every charge carrier is stopped (e.g. for thick shielding). The shielded flux spectra for protons and electrons after 1.85 mm of Al shielding and integrated over a 1-year mission is shown in Fig. 1c, d. Surprisingly, the polar orbit does not have the highest fluence, as spacecrafts with 51.6° inclination spend more time in the SAA than spacecrafts with 98° inclination, similarly for protons and electrons. A spectral distribution with an absence of low-energy protons, as shown in Fig. 1c, is advantageous, because only low-energy particles can deposit significant amounts of energy into the payload. It should be mentioned that the electrons in Fig. 1d do not originate from trapped electrons in the Van Allen belt but rather are secondary electrons produced via ionizing interactions of high-energy protons with the Al atoms in the shielding material.

While the particle fluence spectra are directly accessible through SPENVIS, similar tools for \(\gamma\)-rays do not exist. Gamma-rays mostly originate either directly from the sun or from the radioactive decay of trapped particles. For our study, we use data from the CORONAS-I satellite\(^37\,38\), which mapped the \(\gamma\)-ray flux above the Earth at 500 km altitude (see Table 1).

**Device fabrication and characterization.** Exfoliated hBN flakes have been treated with an oxygen plasma and successively rapidly thermally annealed\(^14\). The oxygen plasma creates point defects in the crystal lattice, which act as trapping sites for localized excitons. The single-photon emitters formed in this way were located and characterized using a confocal microphotoluminescence
(μPL) system equipped with an ultrashort-pulsed laser for time-resolved measurements (see Methods). The emitters are excited off-resonantly at 522 nm, less than half of the bandgap of hBN, resolved measurements (see Methods). The emitters are excited optoelectronics. After transfer to a Si/SiO2 substrate (see Fig.2b), native state as basic building blocks for future electronics and the post-silicon age, we also tested monolayer TMDs in their ON regime of the functional FET device.

The performance of the single-photon emitters in hBN and the bi-exponential from which radiative and non-radiative decay time τr and τnr can be extracted. Every flake is scanned with a 1-μm grid and a spectrum is recorded at each point. To gather enough statistics, a total of 49 monolayer flakes with areas ranging from 60 to 1290 μm² have been characterized. Unless stated otherwise, all optical and electrical measurements have been carried out at RT. More than 80 devices were investigated throughout this study; herein we only show exemplary results and average over the full data set (see Supplementary Notes 2, 5, and 6).

**Gamma-ray tests.** The γ-ray source predominantly used for space qualification is the radioactive isotope 60Co, which emits photons with energies of 1.17 and 1.33 MeV as it decays. Owing to availability, we used the isotope 22Na instead, which decays into 20Ne via the emission of a 1.28 MeV photon, similar to the γ-ray energy from the Co isotope. From its initial nominal activity of 1.04 GBq, a total photon flux of 10.3 MBq cm⁻² s⁻¹ MeV⁻¹ is emitted into the output mode of the Tungsten container in which the source was kept. We placed the samples at distances of d = 10.0(1), 13.0(1), 18.0(1), and 40.0(1) cm from the source output, thus simulating various altitudes and times in orbit (see Supplementary Fig. 1). All samples were irradiated for 2:27 h, meaning that the maximal fluence at the closest distance to the source was \( F_F = 18.41 \times 10^7 \text{cm}^{-2} \text{sr}^{-1} \text{MeV}^{-1} \). Unless stated otherwise, the crystals presented in this section were irradiated with the highest photon flux. Unexposed control samples ensured that any potential changes are solely due to irradiation.

The performance of the single-photon emitters in hBN and the FET devices remained invariant when comparing samples before and after the γ-ray exposure. The zero phonon line (ZPL) of a sample quantum emitter as shown in Fig. 3a peaked initially at 563.78(8) nm with a linewidth of 4.29(13) nm (extracted from fit). Unless stated otherwise, all uncertainties are 95% confidence intervals. After the crystal was irradiated, the ZPL peaked at 563.78(8) nm with a linewidth of 4.29(13) nm (extracted from fit). Similarly, its \( g_0^2 \) did not change (see Fig. 3b) with \( g_0^2 = 0.185(23) \) and \( g_1^2 = 0.188(25) \), where index i and f stand for before and

**Fig. 1** Space environment. Geographical distribution of the trapped a proton and b electron flux at 500 km altitude, calculated with the AP-8 MAX and AE-8 MAX models in SPENVIS, respectively. Integrated annual c proton and d electron fluence after 1.85 mm of Al shielding for typical orbital inclinations.

**Table 1 Summary of total measured gamma-ray flux from the CORONAS-I satellite at 500 km altitude**

| Location    | γ-Ray energy [MeV] | Flux [cm⁻² s⁻¹ sr⁻¹ MeV⁻¹] |
|-------------|--------------------|-----------------------------|
| Equator     | 0.32-1             | 0.079(59)                   |
|            | 1-3                | 0.022(14)                   |
| Polar cap   | 0.32-1             | 0.174(59)                   |
| Polar cap   | 1-3                | 0.095(14)                   |

Full data available in ref. 38.
V shows only slight alteration after irradiation. The shift of the threshold voltage is <0.1 V (dashed line in Fig. 3d). In fact, the standard deviation of the changes in the ON/OFF ratio to temporal variations only. The variations on control samples as well as variations before and after the exposure, respectively. While the quantum emitters already present in the hBN crystal did not change with respect to their optical emission properties, the γ-rays were able to create five new emitters on ~40,000 μm² of crystal area. Thus the probability of creating a second emitter directly adjacent to another is very low. Figure 3c shows the spectrum of one of the newly created emitters. As the crystal was not subsequently annealed, its brightness as well as stability was not as good as for other emitters.14

Comparably, the FETs were also only marginally affected by the γ-rays. Figure 3d shows back gate sweeps for a MoS₂ transistor. The current ON/OFF ratio β was reduced from β₁ = 21,213 to β₂ = 14,863 at a drain-source bias of V₃s = 1 V. While this is a significant change in the ON/OFF ratio, we measured the ON/OFF ratio 5 h later and saw β further reduced to 11,781 (dashed line in Fig. 3d). In fact, the standard deviation of the variations on control samples as well as variations before and after irradiation were roughly 4000. Hence, we attribute these changes in the ON/OFF ratio to temporal variations only. The FETs in general are sensitive to surface adsorption, which causes these temporal variations. In addition, I–V characteristics are highly dependent on the Schottky or contact resistance, which varies across different measurements. However, by varying the drain-source bias from 0.8 to 1.2 V, the initial performance could be restored (see Fig. 3d). Another characteristic of transistors is the I–V curve measured at fixed back gate voltages V_bg. For V_bg = 15 V, this is shown in Fig. 3e and for other V_bg in Supplementary Fig. 2. The I–V curves show no change due to the irradiation. The FETs, while conducting at a particular back gate bias, show no threshold voltage shift with ΔV_th < 0.1 V.

While the 2D material-based devices showed no change after the γ-ray tests, the optical signature of monolayer WS₂ changed remarkably: The monolayer shown in Fig. 2b showed a significant increase in photoluminescence (PL). Moreover, the brightness increased by a factor of 2.99 after being exposed to the γ-rays (see Fig. 4a, b). Furthermore, from the averaged PL spectrum of the monolayer (see Fig. 4c, for details of the averaging algorithm see Supplementary Note 1), we extract that the exciton/trion ratio α changed from 0.706(11) to 1.138(19). Both the exciton and trion emission were enhanced, however, the exciton emission was
enhanced more strongly as the change from $\alpha < 1$ to $\alpha > 1$ shows. This also indicates a change in doping ratio. Given the initial linewidths of 3.80(3) for excitons and 14.07(13) nm for trions, there was no change in center wavelength of the exciton emission (613.89(3) to 613.41(2) nm) and only a slight change of the trion emission (623.45(19) to 619.28(19) nm). However, the linewidths changed to 3.45(2) for excitons and 11.73(13) nm for trions. In addition, the radiative carrier lifetime (see Fig. 4d) had also increased from 336(3) to 678(5) ps. The fit routine deconvolutes the data from the system response. e Long-term stability of the PL spectrum measured at different days. The irradiation took place at day 2. For clarity, each subsequent spectra is shifted by 50 nm. The peak wavelength remained invariant with its mean at 614.65 nm. The mean peak wavelength shifted from 613.89(3) to 613.41(2) nm, and only a slight change of the trion linewidths of 3.80(3) for excitons and 14.07(13) nm for trions, which also indicates a change in doping ratio. Given the initial exciton/trion ratio as well as carrier lifetime with WS2 before and after the irradiation (see Fig.4f, i). Moreover, under the same exposure conditions, the PL had only increased marginally by 1.05 compared to the 2.99 from the WS2 sample presented previously. In addition, the exciton/trion ratio was stable with WS2 before and after the irradiation being 1.328(36) and 1.317 (36) as well as was the carrier lifetime with $\tau_f = 1086(41)$ and $\tau_r = 1071(47)$ (see Fig. 4f, g). It should be mentioned that MoSe2 and WS2 have intrinsically different exciton/trion ratios, since our MoSe2 is a p-type and WS2 is an n-type semiconductor. By averaging over all samples, we found $\alpha_{MoSe2} = 1.252(86)$ and $\alpha_{WS2} = 0.715(117)$ (the uncertainty is the standard deviation).

During the data analysis, we noted that the $\gamma$-radiation dose was higher than intended due to a calculation error. The resulting highest $\gamma$-ray fluence is equivalent to 2170 years at 500 km above the polar caps. However, in terms of space certification this is not an issue. If anything, this further confirms radiation resistance. This proves that 2D materials can withstand even harsher radiation environments than LEO, such as during solar flares or
Backtracing of the healing mechanism. An increase in PL and carrier lifetime is very surprising. Initially, it was expected that radiation could lead to the formation of new defects, but not to defect healing. We note that low-energy X-ray irradiation in oxygen environments can lead to the formation of oxygen-related defects. Although radiation-induced healing of nanomaterials has been reported, such an effect has not been observed with gamma rays, specifically with such remarkable consequences. It is known that the most common defects in exfoliated TMD materials are chalcogen vacancies. Simulations do also predict that these vacancies can chemically react with oxygen, because oxygen itself is a chalcogen. Thus we propose that this healing is due to the chemadsorption of atmospheric oxygen, catalyzed by gamma irradiation. A similar mechanism was proposed in a study involving laser-induced defect healing of WSe₂. The gamma-ray-induced healing observed in our study could happen via several different pathways. One possibility involves the formation of oxygen radicals due to the presence of free electrons from primary reactions like Compton scattering.

To support this, we conducted low-temperature PL measurements of irradiated and control samples at 8 K. The low-temperature environment reduces thermal broadening, which allows the individual emission signature to be resolved. We discovered multiple blue-shifted peaks compared to the RT measurements (see Fig. 5a), most of which are attributed to negatively charged trions. Consistent with standard semiconductor models and experiments, the exciton emission decreases with temperature as the trion emission increases. While both samples exhibit these low-temperature excitonic features, the control sample showed additional PL emission in the red sideband. Therefore, the defect density had decreased six-fold after the 2.08:1 and 0.35:1 for irradiated and control samples, respectively.

Fig. 5 Identification of the gamma-ray induced healing mechanism. a Photoluminescence (PL) spectrum of gamma-irradiated and control samples at 8 K and room temperature. The control sample shows strong defect emission in the red sideband. b Spectrally and time-resolved PL reveals carrier lifetimes close to the system response at 592 and 600 nm and 361(3) ps at 626 nm, confirming excitonic and defect nature of the emission. Unlike for defects, the radiative lifetime for excitons/trions is proportional to temperature. The spectral positions at which the lifetimes were measured are marked with correspondingly colored triangles in c (small inset). c Spectrally resolved power dependence on a log-log plot reveals a slope close to 1 at 592 and 600 nm, indicating excitonic emission, while the slope <1 at 626 nm means the emission originates from defects. The inset shows the positions in the spectrum (marked with the corresponding colors) at which the power dependence is measured. d PL emission prior and subsequent to the inductively coupled plasma treatment shows a similar increase in PL brightness compared to the gamma-irradiated samples. In addition, at low temperature no defect emission becomes visible, confirming that oxygen can passivate vacancies. e Repetition of the gamma-irradiation on SiO₂ and SiC substrates as well as in air and vacuum show that the atmosphere must be the source of oxygen used for the defect healing, most likely through adsorbed oxygen onto the surface. f Density functional theory calculations of the bandstructure of pristine WS₂ (left), WS₂₋ₓ (middle), and WS₂₋ₓOₓ (right) show that, unlike the V₅ defect, the S₀ defect has no unoccupied deep mid-bandgap state. The middle and right bandstructure show the conduction and valence band from the primitive pristine unit cell (solid lines) overlayed with the conduction and valence band from the supercell calculations (dotted lines).
excitons or trions, the slope at 626 nm is \(<1\), which indicates defect emission\(^\text{23}\).

In the next phase of this study, we confirm that the defect healing is oxygen-related. We replicate the optical signature of the \(\gamma\)-ray-exposed samples by treating freshly prepared monolayers with an \(\text{O}_2\) inductively coupled plasma (ICP) and optimizing the plasma parameters (see Methods). Figure 5d shows the PL spectrum prior and subsequent to the ICP treatment at RT and 8 K. Much like the irradiated samples, also the monolayers treated with the oxygen plasma show a strong increase in brightness and no defect emission at low temperature as well as a longer carrier lifetime. Similar PL enhancement through defect engineering and oxygen bonding using mild oxygen plasma treatment of monolayer MoS\(_2\) has been reported previously\(^\text{52}\). While these results uphold the conjecture of oxygen-related defect healing, the oxygen in the \(\gamma\)-ray experiments could either be supplied by atmospheric oxygen or oxygen from the SiO\(_2\) layer. Therefore, we repeated the irradiation with samples on both Si/SiO\(_2\) and SiC substrates in air and under vacuum at 10\(^{-4}\) atm. This will also strongly reduce the amount of surface-adsorbed oxygen. The in-air irradiated samples showed the characteristic increase in brightness and carrier lifetime, while the under-vacuum irradiated samples remained unaffected (see Fig. 5e). We found no dependency on the substrate material. In the context of space certification, this means that WS\(_2\) monolayers in evacuated spacecrafts are also not affected even by excessive \(\gamma\)-radiation.

In addition to the WS\(_2\) crystals, we also exposed MoS\(_2\) and WSe\(_2\) monolayers to gamma-rays (in air). We observed a slight increase in PL intensity and carrier lifetime after the irradiation for WSe\(_2\) (see Supplementary Fig. 8) and no change for MoS\(_2\). It should be mentioned that the PL emission from monolayer MoS\(_2\) in general is much weaker than for other TMDs, so any change is harder to observe. Furthermore, the change in PL and lifetime for the WSe\(_2\) was much weaker than for WS\(_2\), even though both samples experienced the same \(\gamma\)-ray fluence.

We now turn to a theoretical analysis of the electronic structure of the proposed defect using DFT. We calculate the electronic bandstructure (see Methods) for pristine WS\(_2\), WS\(_2\)\(_{\text{x}}\) (with a sulfur vacancy: \(\text{V}_{\text{S}}\)), and WS\(_2\)\(_{\text{x}}\)O\(_{\text{x}}\) (with an oxygen-substituted sulfur atom: \(\text{S}_x\)). The \(\text{V}_{\text{S}}\) defect has a deep unoccupied state in the bandgap (see Fig. 5f, middle). This is consistent with our experimental observations: The sub-state is an acceptor state due to the creation of chalcogen vacancies by knock-on damage, resulting in permanent loss of PL for TMDs. We propose that this is consistent with previous work\(^\text{54}\). Furthermore, Kim et al. found the onset of degradation at a fluence of 10\(^{13}\) cm\(^{-2}\), with strong degradation at 10\(^{14}\) cm\(^{-2}\)\(^\text{-254}\), while Shi et al. found the damage threshold of WSe\(_2\)/SiC heterostructures at 10\(^{16}\) cm\(^{-2}\)\(^\text{252}\). In our case, the proton fluence of 10\(^{13}\) cm\(^{-2}\) corresponds to 1386 years in orbit (at 51.6° inclination and 500 km altitude). The scaling is based on the number of protons. Hence, we conclude that proton irradiation is no concern for 2D materials and devices in LEO.

Finally, we exposed the samples to electrons using a scanning electron microscope (SEM). The damage to 2D materials caused by electrons is mostly displacement and sputtering\(^\text{33}\). Similar to the proton accelerator, both the energy range as well as the integrated flux are beyond the capabilities of the SEM. The tested energies were 5, 10, 20, and 30 keV while the fluence varied from 10\(^{10}\) to 10\(^{15}\) cm\(^{-2}\). At 500 km altitude, the integrated fluences are 12.35, 32.06, and 20.73 \(\times 10^8\) cm\(^{-2}\) for equatorial, ISS, and polar orbit, respectively. At the lowest accessible fluence, which is still three orders of magnitude above what is expected in LEO, the crystals were mostly unaffected by the electron irradiation (see Supplementary Note 6 and Supplementary Fig. 18 through 20). Extrapolating the fluence to LEO levels predict that electrons will not have any impact on 2D materials. Higher electron fluences result in permanent loss of PL for TMDs. We propose that this is due to the creation of chalcogen vacancies by knock-on damage, which, as previously mentioned, cause recombination, thereby quenching the PL\(^\text{35}\). However, if the electron energy is increased from 5 to 30 keV, even at the highest fluence such damage was mitigated. This is because higher-energy electrons have a smaller interaction cross-section (see Supplementary Fig. 12). The single-photon emitters remain unaffected by the electron irradiation; however, at extremely high fluences, the emitter density can be increased significantly\(^\text{17,56}\). In our case, this happened while focusing the SEM on a small crystal part before exposing the full crystals to the electrons. The experienced electron fluence at these positions was up to 10\(^{18}\) cm\(^{-2}\) (see Supplementary Fig. 21).

All radiation tests so far indicate that 2D materials tolerate significant amounts of ionizing radiation, far beyond the requirements for LEO. The question arises, if the radiation resilience is also sufficient for higher altitudes. Using SPENVIS, we calculate the integrated annual particle fluence (integrated over the full energy range) as a function of altitude (see Supplementary Fig. 22).
While the proton fluence always remains nearly two orders of magnitude below the damage onset threshold, the electron fluence exceeds the observed damage onset at altitudes >1000 km. It should be mentioned that these calculations assume the same 1.85 mm of Al shielding as above. The shielding also explains the leap in electron fluence at 2000 km: The electron energy increases with altitude and thus actually trapped electrons can penetrate the shielding. As already mentioned, at lower altitudes the electrons are secondary electrons produced via ionizing interactions of high-energy protons with the shielding. Nevertheless, by using an appropriate shield (5.8 mm graded Al/Ta with a Ta-to-Al mass ratio of 35%), the electron fluence can be kept below the damage threshold. Shielding meeting this requirement is common for higher orbits such as in geostationary satellites. Furthermore, this means that 2D materials also can operate in other environments with heavy irradiation, such as during solar flares or near nuclear reactors.

**Discussion**

We presented a comprehensive study on the effects of radiation on 2D materials in vision of space certification. Moreover, this study covered the effects of γ, proton, and electron irradiation on TMD-based FETs and single-photon sources in hBN as well as their interaction with blank TMD monolayers. These nanomaterials were investigated back to back, shortly before and after irradiation. While all crystals remained effectively invariant during solar flares or near nuclear reactors. In addition, if the TMD and multilayer hBN crystals were optically identified, 100 nm of gold is deposited and then LOR 3A was used for lift-off. The subsequent rapid thermal annealing was done within ±5 keV and the error on the E/kT = 2.603 ± 0.002 eV at 850 °C at a gas pressure of 13 Torr to prevent the formation of ice on the window. The objective was replaced with a Nikon S Plan Fluor ×60/0.7 objective with adjustable correction ring. The second-order correlation function was measured using a Hanbury Brown and Twiss (HBT)-type interferometer in a different confocal set-up with a 512 nm diode laser, equipped with a spectrometer and nano-positioning stage, ensuring that the defects can be localized. The correlation function data are fitted to a three-level system with ground and excited states as well as a meta-stable shelving state:

\[
g^{(2)}(t) = 1 - A e^{-t/t_1} + B e^{-t/t_2}
\]

where \(t_1\) and \(t_2\) are the excited and meta-stable state lifetimes, respectively, \(H\) accounts for different electrical and optical path lengths in the HBT interferometer, and \(A\) and \(B\) are the anti-bunching and bunching amplitudes, respectively. The experimental data have been normalized such that for very long time delays, \(g^{(2)}(\rightarrow) = 1\).

**Electrical characterization.** The FETs were characterized with a Kiehley 4200 Semiconductor Analyzer. One of the the gold electrodes is grounded, while the n+-doped Si substrate functions as a back gate, providing uniform electrostatic doping of the channel. Back gate sweeps at different biases between source and drain were measured as well as V−C curves at various back gate voltages. All electrical measurements were carried out at RT.

**Irradiation.** The radioactive isotope \(^{22}Na\) was used as a γ-ray source and was kept in a sealed Tungsten container, which was opened for the duration of the exposure. For every disintegration, a 1.275-MeV photon is emitted into 4π. With a branching ratio of 99.6%, the electron happens by the transition or electron capture, respectively, resulting in a 90% probability that a positron is emitted. The positrons are shielded by Al foil, where they recombine with electrons to create two γ-rays with energies of 511 keV in opposite directions. The nominal activity was \(A = 1.04\) GBq (number of decays), which together with the container geometry leads to a total photon flux of 10.3 MBq·cm\(^{-2}\)·s\(^{-1}\)·MeV\(^{-1}\) at the output of the container. The differential flux was calculated with

\[
F_E = \sum F_{E_{\gamma}} G_E E_E
\]

with branching ratio \(\Gamma_E\) photon energy \(E\), and geometrical form factor of the container \(G_E\) (which is energy dependent due to the position of the Al foil). The samples were placed at different distances to the source, simulating different altitudes/times in orbit, with a placement accuracy of 1 mm. All samples were mounted facing toward the γ-ray source. The second γ-ray experiment took place 117 days later, after which the source activity decreased to 91.8% (\(t_\gamma = 2.603\) years). We accounted for this by adjusting the distance to the source. We exposed samples in air and in a vacuum chamber at 10\(^{-4}\) atm. The γ-rays were attenuated by the glass window ports of the vacuum chamber by only 5%. This attenuation does not account for the complete disappearance of the healing effect on the samples in the chamber. For the proton irradiation, a high-energy implanter featuring a 1.7 MV tandem Pelletron accelerator was used. TiH was used as target for the ion sputter source and Ti ions were filtered by a 90° magnet. The tandem accelerator can double the maximum ion energy. Energy dependent configuration the proton energy was limited from 200 keV to 2.5 MeV. The ion energy is typically well defined within ±5 keV and the error on the fluence is <±10%. The irradiation took place under pressures of 10\(^{-7}\) Torr at RT. For the electron irradiation, the SEM from an FEI Helios 600 NanoLab was used, allowing for electron energies ranging from 1 to 30 keV at 2.2 nA and RT. The current was varied from 0.17 to 0.69 nA. The electron fluence \(F_E\) is given by \(F_E = \frac{1}{4\pi} E_E t\), where \(E_E\) is the electron current, \(t\) the frame time, \(e\) the electron charge, and \(A\) the frame area. The crystal flakes were located at a very low electron flux and then the SEM was
aligned using another flake nearby, so that the crystal flake under investigation is targeted with a focused electron beam.

**Plasma etching.** We used the commercial ICP-RIE (reactive ion etching) system Samco RIE-400IP and varied all process parameters. We found the optimal process parameters to be 75 W ICP power, 0 W RF power, 3 min plasma interaction time as well as a gas pressure of 6.6 Pa at an oxygen gas flow rate of 30 cm³ min⁻¹. The RF power is chosen zero to avoid any ion bombardment during the plasma exposure, thus ensuring the process is chemical and not physical (this results in crystal etching or thinning). All ICP processes were carried out at RT.

**Computational methods.** The space environment calculations were performed using the SPENVIS web interface. The proton and electron flux spectra were calculated using the AP-8 MAX and AE-8 MAX models. The shielded fluence spectra for 1.833 mm Al shielding were obtained using the MFLUX package. The interactions between charge carriers and matter are calculated using Monte Carlo simulations (see Supplementary Note 4) [57-59]. These simulations take electronic magnetic scattering processes and hadronic nuclear interactions into account. Owing to the more complicated nature of the interactions of electrons with the shielding material, the electron spectrum is less accurate. The DFT calculations have been performed using the ab initio total-energy and molecular-dynamics program VASP (Vienna Ab initio Simulation Package) developed at the Fakultät für Physik at the Universität Wien [60,61]. First, the geometry of the pristine conventional cell was optimized using a 15 × 15 × 1 Monkhorst-Pack reciprocal space grid such that all forces were <0.001 eV Å⁻¹. We used a plane-wave energy cutoff of 450 eV and norm-conserving pseudopotentials with nonlinear core-correction to describe the core electrons. We also used the Perdew–Burke–Ernzerhof (PBE) functional in the generalized gradient approximation to describe the exchange-correlation energy [62]. The monolayer was constructed using a 7 × 7 × 1 supercell of the optimized primitive unit cell. The ionic positions were then relaxed again, while keeping the cell size fixed. We chose the vacuum distance between each layer, described by the lattice parameter c, such that the bandstructure is flat in the direction of the Brillouin zone. This indicates that there is no inter-layer interaction. We used the same method to obtain the bandstructure of the oxygen and vacancy centers in both, WS2 and MoSe2. These calculations show flat bands in each high symmetry direction, which indicates that there is minimal defect–defect interaction between neighboring supercells. The effective bandstructures shown here were unfolded using the PyVaspwfc package [63,64].

When analyzing these calculations, it is important to remember that PBE DFT systematically underestimates the quasiparticle bandgap [65]. Further, verifying the spectra for 1.853 mm Al shielding were obtained using the MFLUX package. The proton and electron etching or thinning). All ICP processes were carried out at RT.

**Data availability**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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**Author contributions**

P.K.L., Y.L. and B.C.B. supervised the project. T.V. and P.K.L. devised the experiments. T.V., K.S., A.S. and L.Z. fabricated and characterized the samples. T.V., P.R. and M.W.D. conducted the theoretical calculations. T.V., J.S. and J.R.M. carried out the irradiation experiments. T.V. and F.K. developed the ICP processes. All authors participated in the result discussions, analysis and the writing of the manuscript.

**Additional information**

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**Competing interests:** The authors declare no competing interests.

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