

## Titanium Trisulfide Nanosheets and Nanoribbons for Field Emission-Based Nanodevices

Pawbake, Amit S.; Khare, Ruchita T.; Island, Joshua O.; Flores, Eduardo; Ares, Jose R.; Sanchez, Carlos; Ferrer, Isabel J.; Van Der Zant, Herre S.J.; Castellanos-Gomez, Andres; More Authors

**DOI**

[10.1021/acsanm.2c03460](https://doi.org/10.1021/acsanm.2c03460)

**Publication date**

2023

**Document Version**

Final published version

**Published in**

ACS Applied Nano Materials

**Citation (APA)**

Pawbake, A. S., Khare, R. T., Island, J. O., Flores, E., Ares, J. R., Sanchez, C., Ferrer, I. J., Van Der Zant, H. S. J., Castellanos-Gomez, A., & More Authors (2023). Titanium Trisulfide Nanosheets and Nanoribbons for Field Emission-Based Nanodevices. *ACS Applied Nano Materials*, 6(1), 44-49.  
<https://doi.org/10.1021/acsanm.2c03460>

**Important note**

To cite this publication, please use the final published version (if applicable).  
Please check the document version above.

**Copyright**

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

**Takedown policy**

Please contact us and provide details if you believe this document breaches copyrights.  
We will remove access to the work immediately and investigate your claim.

# Titanium Trisulfide Nanosheets and Nanoribbons for Field Emission-Based Nanodevices

Amit S. Pawbake,<sup>¶</sup> Ruchita T. Khare,<sup>¶</sup> Joshua O. Island, Eduardo Flores, Jose R. Ares, Carlos Sanchez, Isabel J. Ferrer, Mahendra Pawar, Otakar Frank, Mahendra A. More,<sup>\*</sup> Herre S. J. van der Zant, Andres Castellanos-Gomez,<sup>\*</sup> and Dattatray J. Late<sup>\*</sup>



Cite This: *ACS Appl. Nano Mater.* 2023, 6, 44–49



Read Online

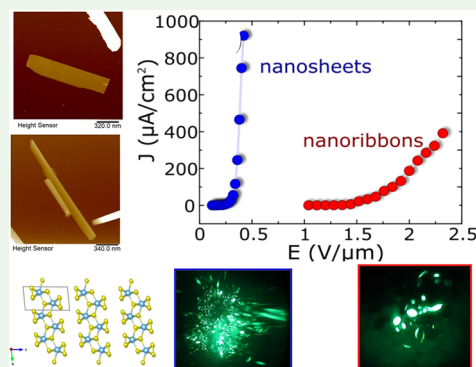
ACCESS |

Metrics & More

Article Recommendations

**ABSTRACT:** The field emission (FE) properties of TiS<sub>3</sub> nanosheets and nanoribbons, synthesized by direct sulfuration of bulk titanium, are investigated. The nanosheets show an enhanced FE behavior with a low turn-on field of  $\sim 0.3$  V/ $\mu\text{m}$ , required for drawing an emission current density of  $\sim 10$   $\mu\text{A}/\text{cm}^2$ . Interestingly, the TiS<sub>3</sub> nanosheet emitter delivered a large emission current density of  $\sim 0.9$  mA/ $\text{cm}^2$  at a relatively low applied electric field of  $\sim 0.4$  V/ $\mu\text{m}$ . We have estimated the values of the field enhancement factor ( $\beta$ ), which are found to be  $\sim 5 \times 10^4$  for the TiS<sub>3</sub> nanosheet emitter and  $\sim 4 \times 10^3$  for the nanoribbon emitter. We attribute the superior FE performance to the presence of atomically sharp edges and the reduced thickness of TiS<sub>3</sub>, as reflected in the high value of  $\beta$ . In fact, the nanosheet sample presents a higher density of ultrathin layers ( $\sim 12$  nm-thick), and thus, they have a larger edge to volume ratio than the nanoribbon samples (which are  $\sim 19$  nm-thick). The superior FE behavior of TiS<sub>3</sub> nanosheets over nanoribbons makes them a propitious field emitter and can be utilized for various FE-based applications, demanding large emission currents and lower operational voltages. Moreover, the FE current stability recorded on these samples confirms their promising performance. Thus, the present investigation brings out a great promise of TiS<sub>3</sub> nanosheets and nanoribbons as field emitters for vacuum nanoelectronics devices.

**KEYWORDS:** TiS<sub>3</sub>, nanosheets, nanoribbon, field emission, current stability



## INTRODUCTION

The synthesis, characterization, and technological applications of one-dimensional (1D) nanostructures, namely, nanorods, nanowires, nanoneedles, and nanobelts, have been a subject of study over the past decade due to their high aspect ratios.<sup>1</sup> One of the lesser explored 1D nanostructures is the nanoribbon structure (partly 1D), which can be used for both fundamental research and technological applications.<sup>1–3</sup> However, the large-scale exercise of 1D nanoforms for device applications still faces challenges and opportunities, such as assembling them in an ordered array form or manufacturing them with uniform dimensions and narrow size dispersion. These limitations, to a certain extent, can be overcome by two-dimensional (2D) nanostructures as their geometries are favorable for designing and realization of novel devices facilitating integration with the present solid-state electronic devices (metal–oxide–semiconductor-based field effect transistors (FETs))<sup>4</sup> To exemplify, very recently, Jia *et al.* comprehensively reviewed the state-of-the-art fabrication techniques for the on-chip integration of 2D materials, along with the current challenges and future perspectives.<sup>5</sup> Furthermore, reproducibility and uniformity of dimensions can be maintained for the 2D structured materials.

In anticipation, layered nanostructures have received immense research interest in the past few years owing to their exceptional properties.<sup>4,5</sup> Particularly, transition metal dichalcogenides (TMDCs), identified as semiconducting 2D layered materials, possess exceptional physicochemical properties and have been realized for many technological applications including optoelectronic devices,<sup>6</sup> gas sensing,<sup>7</sup> and energy storage devices.<sup>8</sup>

Field emission (FE), emission of electrons from a condensed matter phase into vacuum under the application of a strong electrostatic field, has facilitated performance improvement of various vacuum microelectronic devices, particularly the electron microscopes. With the advent of 1D nanostructures, “planar” field emitters (an assembly of nanostructures

**Received:** August 6, 2022

**Accepted:** December 19, 2022

**Published:** January 4, 2023



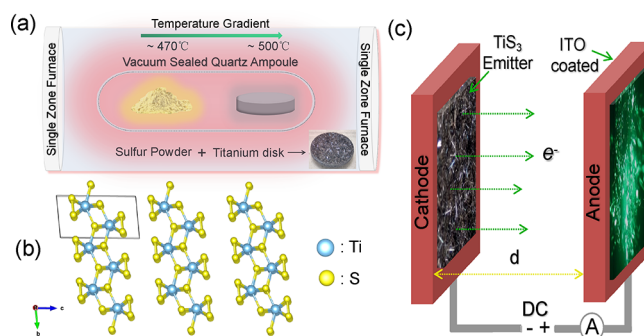
deposited in thin film form on a suitable substrate) are found to be advantageous over conventional single “micro-tip” emitters. Owing to the high “aspect ratio” of the 1D/2D nanostructures, the planar emitters exhibit competency to deliver very high emission current densities at relatively lower applied voltages. The 1D/2D nanostructure-based field emitters have been realized for development of novel nanoelectronics scheme for space applications based on vacuum field emission transistors (VFETs).<sup>4</sup> Although, in principle, every 1D/2D nanostructure possessing a high aspect ratio shows potential as a field emitter and consequently has been investigated, 2D nanostructure-based emitters like graphene,<sup>9</sup> reduced graphene oxide, and their analogous 2D materials (the TMDCs), are observed to possess promising FE behavior.<sup>10</sup> To exemplify, Bartolomeo *et al.* investigated the transfer characteristics of a VFET made up of a single layer WSe<sub>2</sub> on a SiO<sub>2</sub>/Si substrate, which exhibited excellent emission stability (fluctuations  $\leq 5\%$ ) during continuous operation for more than 20 h.<sup>11</sup> These interesting results have motivated further work on alike layered structures, predominantly TMDCs.<sup>11–16</sup>

The transition metal trichalcogenides (TMTCs) represent an important class of materials possessing a unique set of properties and potential for technological applications. Among various TMTCs, titanium trisulfide (TiS<sub>3</sub>) is an *n*-type semiconductor with an optical bandgap of  $\sim 1$  eV.<sup>18</sup> It forms sheets held together by van der Waals forces by parallel chains of triangular prisms. Due to these parallel chains, the material's conductivity is anisotropic between the in planes of the “*a*” and “*b*” axes, resulting in a quasi-1D structure.<sup>17</sup> The thin films of TiS<sub>3</sub> can be obtained by direct reaction of titanium and sulfur in a sealed ampoule.<sup>18</sup> Despite possessing exotic properties and potential for applications in field emission, characterization of TiS<sub>3</sub> nanostructures has not hitherto been attempted.

Here, we report the field emission behavior of both the partial 1D and 2D nanoforms of TiS<sub>3</sub>, nanoribbons and nanosheets, respectively. The sharp tip apex as well as the ultrathin/sharp edges of nanoribbons and nanosheets significantly enhance the local electric field, thereby reducing the operational voltages noticeably. The observed values of turn-on field ( $\sim 0.3$  V/ $\mu\text{m}$ , for an emission current density of  $\sim 10$   $\mu\text{A}/\text{cm}^2$ ) and field required to extract a maximum emission current density ( $\sim 0.3$  V/ $\mu\text{m}$ , for emission current density of  $\sim 10$   $\mu\text{A}/\text{cm}^2$ ) are found to be superior to the earlier reports on 2D nanostructure emitters. Thus, the TiS<sub>3</sub> nanosheets and nanoribbons may serve as propitious materials for practical applications in field emission-based devices, demanding large emission current densities and lower operational voltages.

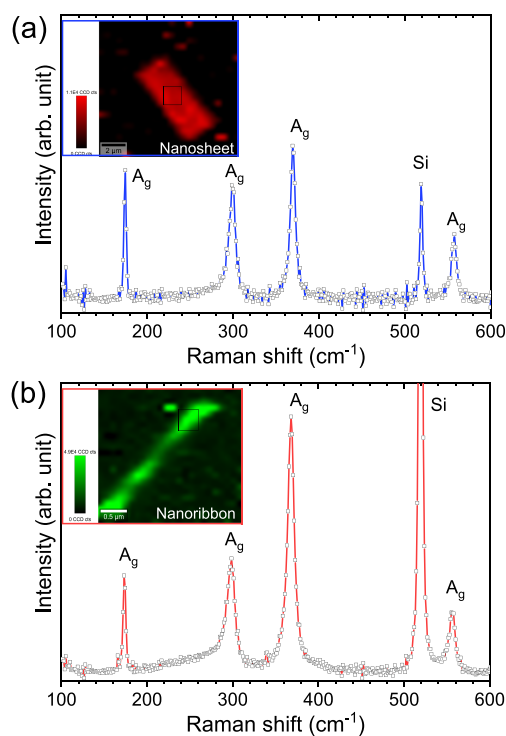
## RESULTS AND DISCUSSION

The schematic illustration of a solid–gas reaction method used for the synthesis of TiS<sub>3</sub> nanosheets and nanoribbons is depicted in Figure 1a. The schematic of a crystal structure for TiS<sub>3</sub> is shown in Figure 1b. As compared to the *a*-axis, the bond length between titanium and sulfur is shorter along the *b*-axis. As a result, strong anisotropic optical and electrical properties are obtained by creating highly conducting chains. Figure 1c represents the schematic illustration of generation of FE images from the TiS<sub>3</sub> emitter. During field emission, electrons emit from the surface of the cathode sample at a negatively biased potential. The emergence of an image potential at the boundary lowers the surface barrier height, resulting in the electron emission occurring easily. The



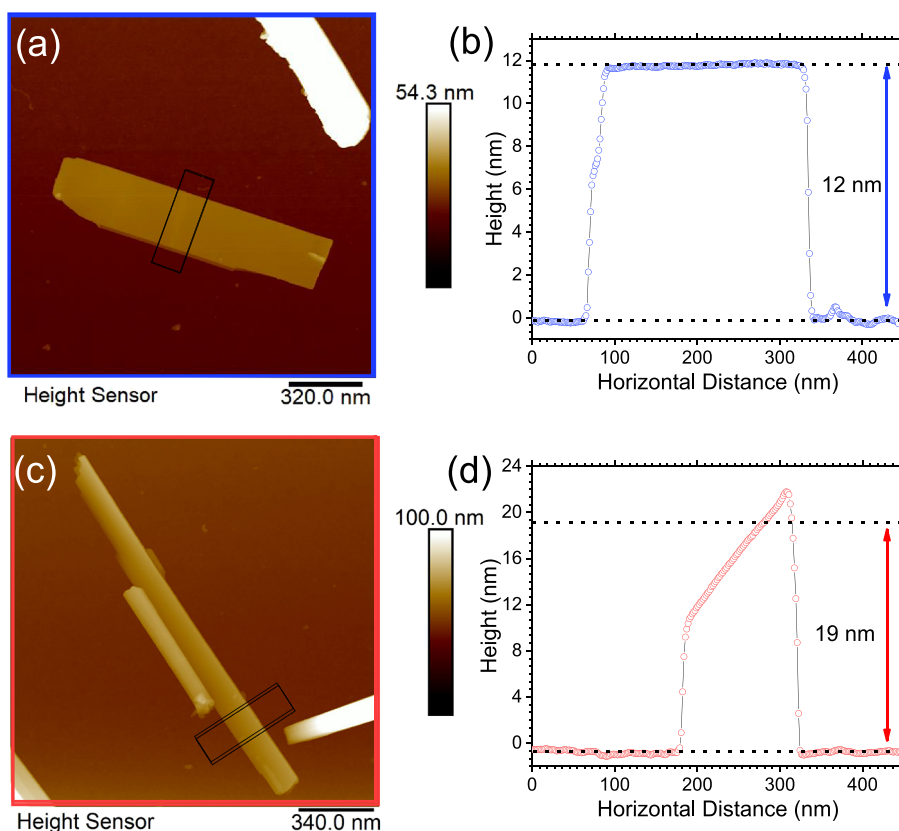
**Figure 1.** Schematic of the (a) vapor transport method involved in the synthesis of TiS<sub>3</sub> nanoribbons. The inset shows an actual zoomed-in view of a sulfured titanium disk. (b) Crystal structure of TiS<sub>3</sub>. The central Ti metal atoms (light blue color) are covalently bonded to six S atoms (yellow color), forming a trigonal prism. These prisms share triangular faces to form 1D chains (shown by dashed lines). (c) Schematic illustration of generation of FE images from the TiS<sub>3</sub> emitter.

crystalline nature of the synthesized nanoribbons and nanosheets was confirmed by Raman spectroscopic analysis. Figure 2a and 1b show the Raman spectra of TiS<sub>3</sub> nanosheets and



**Figure 2.** Comparative Raman spectra of TiS<sub>3</sub> (a) nanosheets and (b) nanoribbon measured with 532.5 nm laser line. The inset shows the respective Raman map, which is generated from the A<sub>g</sub> Raman peak centered at  $\sim 370$   $\text{cm}^{-1}$ .

nanoribbons, respectively, and the insets show the respective Raman mapping images. We observed four intense A<sub>g</sub> Raman phonon modes around 175, 300, 370, and 557  $\text{cm}^{-1}$ , and these are in good agreement with earlier reports.<sup>19,21</sup> The Raman peak at  $\sim 520$   $\text{cm}^{-1}$  is a signature of a silicon substrate. In the Raman spectrum, Raman-active phonon modes oscillate along the *c*-axis perpendicular to the quasi-1D chain, whereas B<sub>g</sub> phonon modes involving atomic displacement along the chain



**Figure 3.** AFM images and AFM height profiles for typical (a, b)  $\text{TiS}_3$  nanosheet and (c, d)  $\text{TiS}_3$  nanoribbon samples.

(*b*-axis) are weak. The increase in lattice spacing of the nanosheets can be attributed to the increased lattice strain; hence, slight intensity and peak position changes are observed in Raman spectra. The detailed lattice vibrational properties and their physical significance were discussed earlier.<sup>19,21,22</sup>

Figure 3a–d shows the AFM images and AFM step height profiles for  $\text{TiS}_3$  nanosheet and nanoribbon samples. The AFM images and height profiles show the typical thicknesses of the nanosheet and nanoribbon,  $\sim 12$  and  $\sim 19$  nm. The thickness measurements were done on several flakes for the nanoribbons, varying from  $\sim 13$  to  $\sim 60$  nm, and for the nanosheets, varying from  $\sim 0.8$  to  $\sim 30$  nm in thickness.<sup>20</sup> The X-ray diffraction,<sup>20</sup> AFM<sup>20</sup>, and transmission<sup>21</sup> and scanning electron microscopy analyses of the  $\text{TiS}_3$  nanosheets and nanoribbons are detailed in our previous work.<sup>19–21</sup>

For the field emission study of  $\text{TiS}_3$  specimens (see the **Methods and Experimental Section**), which were pasted on a copper stub in two different experiments runs: one for the nanosheet specimen and another one for the nanoribbon specimen, a modified Fowler–Nordheim (F-N) equation<sup>23,24</sup> was used for the analysis of field emission current density versus applied electric field data from the F-N plot for  $\text{TiS}_3$  nanoribbon and nanosheet emitters. The modified F-N equation is as follows:

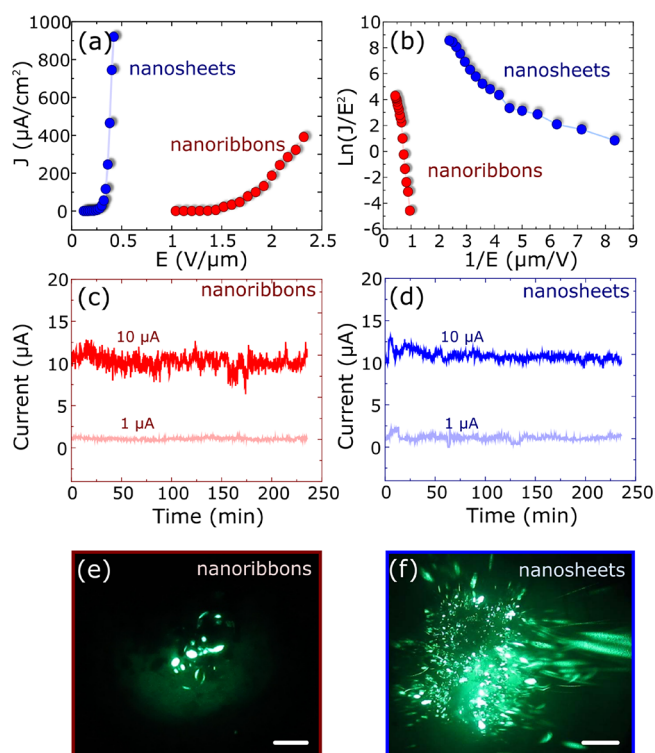
$$J = \lambda_M a \phi^{-1} E^2 \beta^2 \exp\left(-\frac{b\phi^{3/2}}{\beta E} v_F\right) \quad (1)$$

where  $\lambda_M$  is the macroscopic pre-exponential correction factor,  $J$  is the emission current density,  $E$  is the applied average electric field (surface field),  $a$  and  $b$  are constants ( $a = 1.54 \times 10^{-6}$  AeV/V<sup>2</sup>,  $b = 6.83$  eV<sup>-3/2</sup>Vnm<sup>-1</sup>),  $\phi$  is the work function

of the emitter,  $\beta$  is the field enhancement factor, and  $v_F$  (correction factor) is a particular value of the principal Schottky–Nordheim barrier function  $v$ . Figure 4a shows the comparative  $J$ – $E$  plot for the  $\text{TiS}_3$  nanosheet and nanoribbon samples. The values of turn-on and threshold field are defined as the applied electric field required for drawing emission current densities of 10 and 100  $\mu\text{A}/\text{cm}^2$ , respectively. The turn-on field for the  $\text{TiS}_3$  nanosheets and nanoribbons are found to be  $\sim 0.3$  V/ $\mu\text{m}$  and  $\sim 1.4$  V/ $\mu\text{m}$ , respectively. The remarkably low turn-on field of  $\text{TiS}_3$  nanosheets can be attributed to the thin nature and sharp edges of the nanosheets as compared with that of the nanoribbon sample as evident from the AFM images and height profiles (Figure 3). Furthermore, the threshold fields for  $\text{TiS}_3$  nanosheets and nanoribbons are found to be  $\sim 0.4$  V/ $\mu\text{m}$  and  $\sim 1.8$  V/ $\mu\text{m}$ , respectively. The nanostructured geometry of  $\text{TiS}_3$  materials supports (i) a reduced turn-on electric field for the onset of field emission and (ii) a large field-enhancement factor that is attributed to the presence of “sharp nanometric size protrusions” on the edges of the nanostructures. The maximum emission current densities of  $\sim 0.9$  mA/cm<sup>2</sup> were drawn from  $\text{TiS}_3$  nanosheets at an applied electric field of  $\sim 0.4$  V/ $\mu\text{m}$ . For the  $\text{TiS}_3$  nanoribbon sample, the current density increases rapidly with the applied electric field and reaches a maximum value of  $\sim 0.4$  mA/cm<sup>2</sup> at an applied field of  $\sim 2.3$  V/ $\mu\text{m}$ . The corresponding F-N plot is shown in Figure 4b. The F-N curve exhibits a non-linear behavior with saturation at a higher applied electric field. The slope of the F-N curves gives the value of the field enhancement ratio ( $\beta$ ) by the equation

$$\beta = \frac{(-6.8 \times 10^3) \phi^{3/2}}{m} \quad (2)$$





**Figure 4.** Field emission investigations of  $\text{TiS}_3$  nanosheets and nanoribbons. (a)  $J$ - $E$  characteristics. (b) Comparative F-N plot showing non-linear behavior indicating the emission current from the semiconducting emitter. Field emission current stability ( $I$ - $t$ ) plots for (c) nanoribbon and (d) nanosheet emitters. Field emission images recorded at (e)  $\sim 0.3$  mA/cm<sup>2</sup> for  $\text{TiS}_3$  nanoribbons and (f)  $\sim 0.8$  mA/cm<sup>2</sup> for  $\text{TiS}_3$  nanosheets. The scale bar in (e and f) depicts 6  $\mu\text{m}$  length.

In the present case,  $\beta$  was calculated by taking the value of  $\phi$  for  $\text{TiS}_3$  as 4.6 eV.<sup>24,25</sup> The field enhancement factors  $\beta$  for  $\text{TiS}_3$  nanosheets and nanoribbons were calculated by using eq 2 and are found to be  $\sim 5 \times 10^4$  and  $\sim 4 \times 10^3$ , respectively. Such a high value of  $\beta$  for the nanosheets is due to the presence of sharp nanometric size protrusions on their edges, which are responsible for the enhanced field emission behavior. The low value of turn-on and threshold field can be attributed

to the extremely high value of  $\beta$ , suggesting  $\text{TiS}_3$  nanosheets and nanoribbons as promising field emitters. The observed high value of the field enhancement factor is attributed to the presence of sharp protrusions/nanosized features of the emitter surface; the local electric field at the apex of such protrusions gets enhanced. In fact, the observed higher emission current in the  $\text{TiS}_3$  nanosheet sample with respect to the nanoribbon ones aligns well with the higher edge to volume ratio for the nanosheet sample, thereby explaining the enhanced field emission for nanosheet. The enhanced field emission behavior of nanosheets over nanoribbons can also be explained with the help of phonon-assisted electron emission, which is peculiar for materials with monatomic thickness. The FE behaviors of both nanoforms are compared with the existing 1D and 2D materials, and their heterostructures and are given in Table 1. Table 2 shows the comparative values of nanoribbons and nanosheets of  $\text{TiS}_3$  studied in the present case.

**Table 2.** Field Emission Properties of  $\text{TiS}_3$  Nanosheets and Nanoribbons

$\text{TiS}_3$ morphology	turn on field (V/ $\mu\text{m}$ ) at 1 $\mu\text{A}/\text{cm}^2$	turn on field (V/ $\mu\text{m}$ ) at 10 $\mu\text{A}/\text{cm}^2$	maximum emission current density and field	field enhancement factor ( $\beta$ )
nanosheets	$\sim 0.2$	$\sim 0.3$	$\sim 0.9$ mA/cm <sup>2</sup> at $\sim 0.4$ V/ $\mu\text{m}$	$\sim 5 \times 10^4$
nanoribbons	$\sim 1.3$	$\sim 1.4$	$\sim 0.4$ mA/cm <sup>2</sup> at $\sim 2.3$ V/ $\mu\text{m}$	$\sim 4 \times 10^3$

Furthermore, the emission stability is a prior requirement for a material to be the best field emitter. The current stabilities of  $\text{TiS}_3$  nanoribbons and nanosheets were recorded at preset values of 1 and 10  $\mu\text{A}$  for about 3 h, and the corresponding current vs time ( $I$ - $t$ ) curves are shown in Figure 4c,d, respectively. At a lower preset value, the current stability is fairly good, whereas at a higher emission current, small fluctuations can be observed. They result from the adsorption/desorption of residual gas molecules on/from the emitter surface.<sup>32,33</sup> Figure 4e,f shows the field emission micrographs of the nanoribbon and nanosheet emitter samples, respectively.

**Table 1.** Comparison of Field Emission Properties of Reported 1D and 2D Nanomaterials

dimensions of nanofield emitters	field emitter material	synthesis route of material	turn on field (V/ $\mu\text{m}$ ) at 10 $\mu\text{A}/\text{cm}^2$	field enhancement factor	stability and fluctuations	reference
1D	CdS nanowires	thermal evaporation	9	550		26
	ZnS nanowires	thermal evaporation	2.9	2700	<0.8%	27
	Si nanocone	RF sputtering	13			28
	graphene nanoribbon	unzipping MWCNTs	5.8	818	3 h, <7%	29
	$\text{TiS}_3$ nanoribbons	sulfuration of titanium	$\sim 1.4$	$\sim 4 \times 10^3$	3 h, <8%	present work
2D (nanosheets)	$\text{MoS}_2$	solution method	3.5	1138		12
	$\text{WS}_2$	hydrothermal	4.4	2468		15
	$\text{SnS}_2$	hydrothermal	5.9	3200		16
	$\text{VS}_2$	hydrothermal	5.01	2500		14
	CuS	solvochemical	2.05	7261		30
	$\text{TiS}_3$ nanosheets	sulfuration of titanium	$\sim 0.3$	$\sim 5 \times 10^4$	3 h, <10%	present work
3D nanoheteroarchitecture	$\text{GdB}_6$	PLD	2.3 at 1 $\mu\text{A}/\text{cm}^2$	2860		31

The field emission micrograph reflects the symmetry and work function variation of TiS<sub>3</sub> nanosheet and nanoribbon emitter surfaces.

## CONCLUSIONS

In conclusion, the low turn-on fields of  $\sim 0.3$  and  $\sim 1.4$  V/ $\mu\text{m}$  were observed in the case of TiS<sub>3</sub> nanosheet and nanoribbon samples, respectively, required to draw an emission current density of  $\sim 1$   $\mu\text{A}/\text{cm}^2$ . Interestingly, the high field enhancement factor of  $\sim 5 \times 10^4$  was observed for the TiS<sub>3</sub> nanosheet sample, which indicates field emission current from nanometer-scaled features. The field emission current stability for TiS<sub>3</sub> nanosheet and nanoribbon samples indicates the great potential for field emission-based device applications. The low turn-on fields and high field enhancement factors can make the TiS<sub>3</sub> nanosheets and nanoribbons potential candidates for field emission-based nanodevices.

## METHODS AND EXPERIMENTAL SECTION

TiS<sub>3</sub> nanoribbons and nanosheets were synthesized by heating sulfur powder (99.99% purity) in a vacuum-sealed ampoule with Ti powder at 550 and 400 °C to provide sulfur gas for the solid–gas reaction.<sup>19–21</sup> The AFM tapping mode images were recorded using a Bruker Dimension Icon instrument. Raman spectra and mapping on TiS<sub>3</sub> nanostructures were recorded in backscattering geometry using the WITec alpha 300 R system with 532.5 nm excitation and 0.5 mW power. The field emission experiments of TiS<sub>3</sub> nanoribbons and nanosheets were carried out in separate experimental batches in a UHV chamber evacuated to a base pressure of  $\sim 1 \times 10^{-8}$  mbar in the close proximity setup consists of a specimen (TiS<sub>3</sub> nanosheets or nanoribbons that were sprinkled over carbon tape size  $\sim 5$  mm  $\times$  5 mm) as a cathode and copper rod as an anode. The detailed description of the FE system is reported earlier.<sup>31,32</sup>

## AUTHOR INFORMATION

### Corresponding Authors

**Mahendra A. More** – Center for Advanced Studies in Materials Science and Condensed Matter Physics, Department of Physics, University of Pune, Pune 411007, India; Email: [mam@physics.unipune.ac.in](mailto:mam@physics.unipune.ac.in)

**Andres Castellanos-Gomez** – Materials Science Factory, Instituto de Ciencia de Materiales de Madrid (ICMM-CSIC), Madrid E-28049, Spain; [orcid.org/0000-0002-3384-3405](https://orcid.org/0000-0002-3384-3405); Email: [andres.castellanos@csic.es](mailto:andres.castellanos@csic.es)

**Dattatray J. Late** – Centre for Nanoscience and Nanotechnology, Amity University Maharashtra, Mumbai, Panvel 410206, India; [orcid.org/0000-0003-3007-7220](https://orcid.org/0000-0003-3007-7220); Email: [datta099@gmail.com](mailto:datta099@gmail.com), [djlate@mum.amity.edu](mailto:djlate@mum.amity.edu)

### Authors

**Amit S. Pawbake** – J. Heyrovský Institute of Physical Chemistry, Czech Academy of Sciences, 182 23 Prague, Czech Republic; [orcid.org/0000-0002-6345-489X](https://orcid.org/0000-0002-6345-489X)

**Ruchita T. Khare** – Center for Advanced Studies in Materials Science and Condensed Matter Physics, Department of Physics, University of Pune, Pune 411007, India

**Joshua O. Island** – Department of Physics and Astronomy, University of Nevada Las Vegas, Las Vegas, Nevada 89154, United States; [orcid.org/0000-0002-6074-9414](https://orcid.org/0000-0002-6074-9414)

**Eduardo Flores** – Departamento de Física Aplicada, Centro de Investigación y de Estudios Avanzados, Unidad Mérida, 97310 Mérida, Yucatan, México

**Jose R. Ares** – Materials of Interest in Renewable Energies Group (MIRE Group), Dpto. de Física de Materiales,

Universidad Autónoma de Madrid (UAM), 28049 Madrid, Spain; [orcid.org/0000-0001-5238-1800](https://orcid.org/0000-0001-5238-1800)

**Carlos Sanchez** – Materials of Interest in Renewable Energies Group (MIRE Group), Dpto. de Física de Materiales, Universidad Autónoma de Madrid (UAM), 28049 Madrid, Spain; [orcid.org/0000-0001-9816-4537](https://orcid.org/0000-0001-9816-4537)

**Isabel J. Ferrer** – Materials of Interest in Renewable Energies Group (MIRE Group), Dpto. de Física de Materiales, Universidad Autónoma de Madrid (UAM), 28049 Madrid, Spain; [orcid.org/0000-0003-2125-5865](https://orcid.org/0000-0003-2125-5865)

**Mahendra Pawar** – Physical & Materials Chemistry Division, CSIR-National Chemical Laboratory, Pune 411008, India

**Otakar Frank** – J. Heyrovský Institute of Physical Chemistry, Czech Academy of Sciences, 182 23 Prague, Czech Republic; [orcid.org/0000-0002-9661-6250](https://orcid.org/0000-0002-9661-6250)

**Herre S. J. van der Zant** – Kavli Institute of Nanoscience, Delft University of Technology, 2628 CJ Delft, The Netherlands; [orcid.org/0000-0002-5385-0282](https://orcid.org/0000-0002-5385-0282)

Complete contact information is available at: <https://pubs.acs.org/10.1021/acsnm.2c03460>

### Author Contributions

†A.S.P. and R.T.K. contributed equally to this work

### Author Contributions

D.J.L. and A.C.-G. conceptualized this project. A.S.P., R.T.K., J.O.I., E.F., J.R.A., C.S., I.J.F., M.P., O.F., M.A.M., H.S.J.Z., A.C.-G., and D.J.L. prepared and characterized the materials. A.S.P. and R.T.K. performed the field emission measurements of TiS<sub>3</sub> nanoribbon and nanosheet samples and processed the data. A.S.P. prepared all schematic representations. All authors analyzed and discussed the data. M.A.M., A.C.-G., and D.J.L. wrote the first draft of the manuscript, with all authors commenting and editing the manuscript.

### Notes

The authors declare no competing financial interest.

## ACKNOWLEDGMENTS

D.J.L. would like to thank Prof. C. N. R. Rao (FRS), JNCASR and ICMS Bangalore (India) and Prof. Vinayak P. Dravid (Northwestern University, USA) for encouragement and support. The authors thank Director CSIR-National Chemical Laboratory Pune (India) for the support. This work was supported by the Dutch Organization for Fundamental research (NWO/FOM). Mire group acknowledges F. Moreno for technical support. O.F. acknowledges the support of the Czech Science Foundation Project No. 20-08633X.

## REFERENCES

- (1) Island, J. O.; Molina-Mendoza, A. J.; Barawi, M.; Biele, R.; Flores, E.; Clamagirand, J. M.; Ares, J. R.; Sánchez, C.; van der Zant, H. S. J.; D'Agosta, R.; Ferrer, I. J.; Castellanos-Gomez, A. Electronics and Optoelectronics of Quasi-1D Layered Transition Metal Trichalcogenides. *2D Mater.* **2017**, *4*, 22003.
- (2) Hughes, W. L.; Wang, Z. L. Nanobelts as nanocantilevers. *Appl. Phys. Lett.* **2003**, *82*, 2886.
- (3) Arnold, M. S.; Avouris, P.; Pan, Z. W.; Wang, Z. L. Field-effect transistors based on single semiconducting oxide nanobelts. *J. Phys. Chem. B* **2003**, *107*, 659–663.
- (4) Han, J. W.; Moon, D. I.; Meyyappan, M. Cofabrication of vacuum field emission transistor (VFET) and MOSFET. *IEEE Trans. Nanotechnol.* **2014**, *13*, 464–468.

- (5) Jia, L.; Wu, J.; Zhang, Y.; Qu, Y.; Jia, B.; Chen, Z.; Moss, D. J. Fabrication Technologies for the On-Chip Integration of 2D Materials. *Small Methods* **2022**, *6*, 2101435.
- (6) Ganatra, R.; Zhang, Q. Few-Layer MoS<sub>2</sub>: A Promising Layered Semiconductor. *ACS Nano* **2014**, *8*, 4074–4099.
- (7) Wu, S. X.; Zeng, Z. Y.; He, Q. Y.; Wang, Z. J.; Wang, S. J.; Du, Y. P.; Yin, Z. Y.; Sun, X. P.; Chen, W.; Zhang, H. Electrochemically Reduced Single-Layer MoS<sub>2</sub> Nanosheets: Characterization, Properties and Sensing Applications. *Small* **2012**, *8*, 2264–2270.
- (8) Huang, X.; Qi, X. Y.; Boey, F.; Zhang, H. *Chem. Soc. Rev.* **2012**, *41*, 666.
- (9) Ye, D.; Moussa, S.; Ferguson, J. D.; Baski, A. A.; El-Shall, M. S. Highly Efficient Electron Field Emission from Graphene Oxide Sheets Supported by Nickel Nanotip Arrays. *Nano Lett.* **2012**, *12*, 1265–1268.
- (10) Li, Y. B.; Bando, Y.; Golberg, D. MoS<sub>2</sub> Nanoflowers and Their Field-Emission Properties. *Appl. Phys. Lett.* **2003**, *82*, 1962–1964.
- (11) Bartolomeo, A.; Urban, F.; Passacantando, M.; McEvoy, N.; Peters, L.; Iemmo, L.; Luongo, G.; Romeo, F.; Giubileo, F. A WSe<sub>2</sub> Vertical Field Emission Transistor. *Nanoscale* **2019**, *11*, 1538–1548.
- (12) Kashid, R. V.; Late, D. J.; Chou, S. S.; Huang, Y.-K.; De, M.; Joag, D. S.; More, M. A.; Dravid, V. P. Enhanced field-emission behavior of layered MoS<sub>2</sub> sheets. *Small* **2013**, *9*, 2730–2734.
- (13) Song, C.; Yu, K.; Yin, H.; Fu, H.; Zhang, Z.; Zhang, N.; Zhu, Z. Highly efficient field emission properties of a novel layered VS<sub>2</sub>/ZnO nanocomposite and flexible VS<sub>2</sub> nanosheet. *J. Mater. Chem. C* **2014**, *2*, 4196–4202.
- (14) Rout, C. S.; Khare, R.; Kashid, R. V.; Joag, D. S.; More, M. A.; Lanzillo, N. A.; Washington, M.; Nayak, S. K.; Late, D. J. Metallic Few-Layer Flowerlike VS<sub>2</sub> Nanosheets as Field Emitters. *Eur. J. Inorg. Chem.* **2014**, *2014*, 5331–5336.
- (15) Rout, C. S.; Joshi, P. D.; Kashid, R. V.; Joag, D. S.; More, M. A.; Simbeck, A. J.; Washington, M.; Nayak, S. K.; Late, D. J. Superior field emission properties of layered WS<sub>2</sub>-RGO nanocomposites. *Sci. Rep.* **2013**, *3*, 3282.
- (16) Rout, C. S.; Joshi, P. D.; Kashid, R. V.; Joag, D. S.; More, M. A.; Simbeck, A. J.; Washington, M.; Nayak, S. K.; Late, D. J. Enhanced field emission properties of doped graphene nanosheets with layered SnS<sub>2</sub>. *Appl. Phys. Lett.* **2014**, *105*, No. 043109.
- (17) Gorlova, I. G.; Zybtev, S. G.; Pokrovskii, V. Y.; Bolotina, N. B.; Verin, I. A.; Titov, A. N. Nonlinear Conductivity of Quasi-One-Dimensional Layered Compound TiS<sub>3</sub>. *Phys. B* **2012**, *407*, 1707–1710.
- (18) Murray, J. L. The S–Ti (Sulfur-Titanium) System. *Bull. Alloy Phase Diagrams* **1986**, *7*, 156–163.
- (19) Mishra, K. K.; Ravindran, T. R.; Island, J. O.; Flores, E.; Ares, J. R.; Sanchez, C.; Ferrer, I. J.; van der Zant, H. S. J.; Pawbake, A.; Kanawade, R.; Castellanos-Gomez, A.; Late, D. J. Raman Fingerprint of Pressure-Induced Phase Transitions in TiS<sub>3</sub> Nanoribbons: Implications for Thermal Measurements under Extreme Stress Conditions. *ACS Appl. Nano Mater.* **2020**, *3*, 8794–8802.
- (20) Island, J. O.; Barawi, M.; Biele, R.; Almazán, A.; Clamagirand, J. M.; Ares, J. R.; Sánchez, C.; van der Zant, H. S. J.; Álvarez, J. V.; D'Agosta, R.; et al. TiS<sub>3</sub> Transistors with Tailored Morphology and Electrical Properties. *Adv. Mater.* **2015**, *27*, 2595–2601.
- (21) Pawbake, A. S.; Island, J. O.; Flores, E.; Ares, J. R.; Sanchez, C.; Ferrer, I. J.; Jadhkar, S. R.; van der Zant, H. S. J.; Castellanos-Gomez, A.; Late, D. J. Temperature-Dependent Raman Spectroscopy of Titanium Trisulfide (TiS<sub>3</sub>) Nanoribbons and Nanosheets. *ACS Appl. Mater. Interfaces* **2015**, *7*, 24185–24190.
- (22) Wu, K.; Torun, E.; Sahin, H.; Chen, B.; Fan, X.; Pant, A.; Parsons Wright, D.; Aoki, T.; Peeters, F. M.; Soignard, E.; Tongay, S. Unusual Lattice Vibration Characteristics in Whiskers of the Pseudo-One-Dimensional Titanium Trisulfide TiS<sub>3</sub>. *Nat. Commun.* **2016**, *7*, 12952.
- (23) Panda, S. K.; Datta, A.; Sinha, G.; Chaudhuri, S.; Chavan, P. G.; Patil, S. S.; More, M. A.; Joag, D. S. Synthesis of Well-Crystalline GaS Nanobelts and Their Unique Field Emission Behavior. *J. Phys. Chem. C* **2008**, *112*, 6240–6244.
- (24) Ma, J. J.; Liu, X. Y.; Cao, X. J.; Feng, S. H.; Fleet, M. E. Bundle of Nanobelts Up to 4 cm in Length: One-Step Synthesis and Preparation of Titanium Trisulfide (TiS<sub>3</sub>) Nanomaterials. *Eur. J. Inorg. Chem.* **2006**, *3*, 519.
- (25) Wu, X. C.; Tao, Y. R.; Gao, Q. X. Preparation and field emission properties of titanium polysulfide nanobelt films. *Nano Res.* **2009**, *2*, 558–564.
- (26) Li, G. H.; Jiang, Y.; Zhang, Y. G.; Lan, X. Z.; Zhai, T. Y.; Yi, G. C. High-Performance Photodetectors and Enhanced Field-Emission of CdS Nanowire Arrays on CdSe Single-Crystalline Sheets. *J. Mater. Chem. C* **2014**, *2*, 8252–8258.
- (27) Chen, Z. G.; Cheng, L.; Zou, J.; Yao, X.; Lu, G. Q.; Cheng, H. M. Zinc sulfide nanowire arrays on silicon wafers for field emitters. *Nanotechnology* **2010**, *21*, No. 065701.
- (28) Shang, N. G.; Meng, F. Y.; Au, F. C. K.; Li, Q.; Lee, C. S.; Bello, I.; Lee, S. T. Fabrication and Field Emission of High-Density Silicon Cone Arrays. *Adv. Mater.* **2002**, *14*, 1308–1311.
- (29) Khare, R.; Shinde, D. B.; Bansode, S.; More, M. A.; Majumder, M.; Pillai, V. K.; Late, D. J. Graphene nanoribbons as prospective field emitter. *J. Appl. Phys. Lett.* **2015**, *106*, 23111.
- (30) Song, Z.; Lei, H.; Li, B.; Wang, H.; Wen, J.; Li, S.; Fang, G. Enhanced field emission from in situ synthesized 2D copper sulfide nanoflakes at low temperature by using a novel controllable solvothermal preferred edge growth route. *Phys. Chem. Chem. Phys.* **2015**, *17*, 11790–11795.
- (31) Suryawanshi, S. R.; Singh, A. K.; Deo, M.; Late, D. J.; Sinha, S.; More, M. A. 3D Hetero-architecture of GdB<sub>6</sub> nanoparticles on lessened cubic Cu<sub>2</sub>O nanowires: enhanced field emission behaviour. *CrystEngComm* **2015**, *17*, 3936.
- (32) Late, D. J.; More, M. A.; Misra, P.; Singh, B. N.; Kukreja, L. M.; Joag, D. S. Field Emission Studies of Pulsed Laser Deposited LaB<sub>6</sub> Films on W and Re. *Ultramicroscopy* **2007**, *107*, 825–832.
- (33) Zhang, H.; Jimbo, Y.; Niwata, A.; Ikeda, A.; Yasuhara, A.; Ovidiu, C.; Kimoto, K.; Kasaya, T.; Miyazaki, H.; Tsujii, N.; Wang, H. High-endurance micro-engineered LaB<sub>6</sub> nanowire electron source for high-resolution electron microscopy. *Nat. Nanotechnol.* **2021**, *8*, 1–6.