Project progress/ completion Report

1.	DST reference No.	CRD/2020/000197	
2.	Project title	Realizing proximity effect in superconductor/semiconductor-ferromagnet van der Waals heterostructure.	
3.	Objectives	1.Fabrication of van der Waals heterostructure, superconductor: TMDC (NbSe2, NbS2, TaTe2 etc)-CrBr3 heterostructure and semiconductor: TMDC (WS2, MoS2, MoSe2 etc)-CrBr3 heterostructure experimentally via physical method. 2.Modelling of van der Waals heterostructure (superconductor-ferromagnet, semiconductor- fer-romagnet) and optimizing the interfacial distance in such a way so that proximity effect can be established using first-principle simulations. 3.Development of 2D heterostructure based nanocomposites as efficient electrode materials with potential application in energy storage and conversion devices. 4.Generation of spin-polarized current via proximity effect and calculation of diffusion constant from one layer to another layer in van der Waals heterostructure leading to spin injection phe-nomena applicable for engineering devices. 5.Establishing proximity effect experimentally in superconductor/semiconductor-CrBr3 hetero-structure via Zeeman spin hall effect and non-local measurements. 6.Characterization of developed heterostructure to study the influence of microstructural, elec-tronic, topological, electrochemical and magnetic features on its properties. 7.To compute the magnetic condensate and discuss the symmetry-breaking phenomena as well as the spin-rotation and magnetization of each valley of the material for possible potential appli-cations.	
4.	Field of S&T covered under the project	Quantum materials and energy storage	
5.	Project participants		
	Indian side	Foreign side	
	Anil Kumar Singh	Dr. Ramesh Kasi	
6.	Date of start of the project	16/09/2021	
	Date of completion	15/09/2023	
7.	Visits undertaken (please include the number and duration of respective visits)		
		Name & Address of the visiting scientist	Duration of the visit
	India to ASEAN MS	1. Name: ANIL KUMAR SINGH, Research scholar, Dept. of Physics, Tezpur University, Naapam, 784028, Sonitpur. He had visited both the collaborating countries i.e., Singapore (30 days) and Malaysia (30 days). 1. Name: Prof. Pritam Deb, Professor, Dept. of Physics, Tezpur University, Naapam, 784028, Sonitpur. He had visited both the collaborating countries i.e., Singapore (9 days) and Malaysia (15 days).	1. 60 days 2. 24 days

	ASEAN MS to India	1. Dr. Ramesh T Subramaniam Professor, Dept. of Physics Faculty of Science, 50603, Kuala Lumpur, Malaysia. 2. Dr. Ramesh Kasi, Assoc. Professor, Dept. of Physics Faculty of Science, 50603, Kuala Lumpur, Malaysia.	1. 6 days 2. 6 days

8. Yearly Project milestones

The research outcomes of the ASEAN project host potential application in different emerging fields of energy storage, energy conversion, Magnetic resonance imaging (MRI), spintronic devices etc. This leads to the new cutting-edge technologies with low-dimensionality, higher accuracy, affordability, bio-compatibility along with advancement of the existing technologies. We would like to inform you that we have published Eight (8) papers in reputed peer reviewed international journals and Four papers are under communication. We have also presented our research work at National conferences namely as DAE-SSPS 2023 and CM DAYS 2023. In this regard one conference paper is also under communication. Moreover, the project participant and Lead PI from India have successfully completed the visits to collaborating institutes (Singapore and Malaysia) to explore future prospects. The project participant and PI from Malaysia also visited Tezpur University, India to further strengthened the collaboration among the two countries.

Year I: The collaborating institutes (Tezpur university, NTU Singapore and University of Malaysia) jointly performs experimental and theoretical characterizations to fabricate suitable low-dimensional materials with strong magnetic proximity effect. This joint venture leads to nanostructures and hybrid heterostructure systems with enhanced physical properties, chemical properties, electronic properties, memory effect etc., that can be incorporated in room temperature spin valve devices, energy storage devices, MR imaging devices etc. It is worthwhile to mention that we have jointly published four (4) papers in peer reviewed international journals in the first financial year. The Lead PI and project participant have completed all the sanctioned visits to ASEAN countries from India.

Year II: The visits to the collaborating institutes further strengthen the ongoing joint research works and opens new future prospects. This provides access to the state-of-the-art facilities, which expand the scope of our research activities. These visits helped us to exchange data, samples, and resources, which enables us to validate the robustness and reliability of our research findings. By leveraging these collaborative advantages, we are able to design and engineer quantum materials in controlled environment with optimized properties. In this regard, the designed FGT based spin valve devices host room temperature tunable tunnelling magnetoresistance, which can be incorporated into magnetic random access memory devices (MRAM). On the other hand, the developed ensemble of Isotropic Nanoparticles (CEIN) of zinc ferrite exhibits enhanced transverse MR- contrast efficacy. Nonetheless, the developed electroactive materials such as $NiCo_2O_4$/NiO/rGO (CNOG), CNOT etc., hosts outstanding characteristics of energy storage and conversion. Noticeably, these scientific research works leads to publications in international journals. Quantitatively, we have published four (4) papers in the second year along with four (4) papers under communication. Those publication details are mentioned under progress of the project section.

Hence, we are hopeful that the outcomes of this joint scientific venture have addressed various ongoing societal issues such as energy crisis, clinical diagnosis, compact spintronic devices with high efficiency etc. Also, this joint scientific research work fosters networking opportunities and potential future collaborations, which stimulates interdisciplinary collaborations that can lead to novel insights and discoveries.

9. Progress of the Project:

Accomplishment Status: (vis-à-vis the project objectives and milestones, highlighting the major/salient achievements): (Up-to 1 page)	It is worthwhile to mention that we have published **Ten (10)** papers in peer reviewed international journals and **Two (2)** papers are under communication with proper acknowledgement. Also, we have successfully completed our visits to collaborating institutes to explore future prospects. **Spintronics:** As mentioned in the approved objectives, we have successfully fabricated and designed 2D nanocomposites, vdW heterostructures by incorporating both experimental and density functional theory approach in order to realize exceptional proximity effect. In this regard, we have developed Fe3GeTe2/WSe2/ Fe3GeTe2 vertical vdW heterostructures, which results in large tunable tunnelling magnetoresistance (TMR) due to energy dependent spin polarization. Quantitatively, we have observed sign flipping in TMR values, which is found to be -100% at 0.1 eV. Importantly, the

	other spin valve device (Fe3GaTe2/WSe2/ Fe3GaTe2) exhibits room temperature tunable TMR via DC bias, which provides a new perspective on realizing room-temperature vdW functional spintronic devices. Moreover, the designed 1T'-WTe2/CrBr3 vdW heterostructure possesses band-structure modulation, which results in half-metallic character via robust magnetic proximity effect. Also, the modelled structure shows 4% enhancement in total magnetic moments alongwith electrically tunable electronic structure. These findings offer efficient spin injection phenomena in developing electric field mediated spin-filter as well as dual gate field transistor. **Energy storage and conversion:** Further, a versatile electrode material NiCo2O4/NiO/rGO (CNOG) is developed for methanol oxidation and supercapacitor. The low conductivity and problem of aggregation of transition metal oxides are compensated by making a nanocomposite of NiCo2O4/NiO with conducting reduced graphene oxide. High surface area, mesoporosity and conductivity of the hybrid enhance its electrochemical activity. The hybrid electrode offers less charge transfer resistance due to this synergistic effect. Thus, an efficient electroactive material CNOG is developed which is capable of converting and storing energy. In addition, we developed a versatile electroactive material CNOT to explore the synergistic effect of redox-site enriched NiCo2O4 and NiO, with high surface area, hydrophilicity and conductivity of MXene. The high concentration of surface adsorbed redox sites leads to high methanol current density with low onset potential and low overpotential. The presence of both EDLC (MXene) and pseudocapacitive (NiCo2O4 and NiO) component in CNOT, makes it a potential supercapacitive electrode. Hence, CNOT acts as a bifunctional electroactive material for methanol catalysis and high-performance quasi-solid state symmetric supercapacitor. Nonetheless, we have incorporated thermoelectric effect and magnetism in a single moiety in the engineered ML-CrI3/1T-MoS2 heterostructure via magnetic proximity effect. The strong magnetic proximity leads to exotic electronic properties and augmented thermal properties with exceptional electrical control. The observed efficient electrical control manifests non-linear anomalous Nernst effect via change in Fermi energy and magnetic anisotropy energy in presence of an external biasing. Moreover, we have incorporated twist degree of freedom in the designed vdW heterostructure, which results in microscopic electronic structure modulation. These observed findings suggest augmented thermoelectric behavior via the twist proximity. **MR imaging:** We show that structure-correlated MRI-contrast efficiency can be understood by considering complex ensembles with varied spatial arrangement of nanoparticles. The randomly oriented easy axes in Compact Ensemble of Isotropic Nanoparticles (CEIN) of zinc ferrite with enhanced anisotropy energy induces enhancement in transverse MR-contrast efficacy alongwith a high value of longitudinal (r1)/transverse (r2) relaxivity ratio. However, partial aligned easy axes with lower anisotropy also leads to enhancement in transverse MR-contrast efficacy as observed in system hollow core ensemble (HCE). Reduction in transverse MR-contrast efficiency is found in the core−shell ensemble, where we observe highly anisotropic energy barriers. Moreover, the presence of various easy axes orientation in complex structure attributes enhanced anisotropic nature, leading to giant spin−spin relaxometry behavior.
List of joint research publications (Please attach copies)	**1.** Anil Kumar Singh, Weibo Gao, Pritam Deb, Large thermoelectric transport in magnetically coupled CrI_3/1T-MoS_2 vdW heterostructure via spin-charge interconversion. Journal of Physics: Condensed Matter 36(2024), 305704. **Impact factor: 2.7, CiteScore: 4.6.** **2.** Anil Kumar Singh, Weibo Gao, Pritam Deb, Twist proximity endowed large figure of merit in band modulated CrI_3/1T-MoS_2 moiré superlattice. **ACS Applied Materials & Interfaces 2024. Impact factor: 9.5, CiteScore: 15.7.** **3.** Anil K. Singh, W. Gao, P. Deb, Tunable long-range spin transport in a

	van der Waals $Fe_3GeTe_2/WSe_2/Fe_3GeTe_2$ spin valve. Physical Chemistry Chemical Physics 26(2024) 895-902. **Impact factor: 3.3, CiteScore: 5.9.** **4.** Pan, H., Singh, A. K., Zhang, C., Hu, X., Shi, J., An, L., Deb, P., & Gao, W. (2024). Room-temperature tunable tunneling magnetoresistance in $Fe_3GaTe_2/WSe_2/Fe_3GaTe_2$ van der Waals heterostructures. InfoMat, e12504. **Impact factor: 22.7, CiteScore: 35.6.** **5.** K Baruah, S Nandi, M Pershaanaa, K Ramesh, S Ramesh, P Deb, A versatile non-precious metal-based electrode material endowed by layer-on-layer structure for methanol oxidation and supercapacitor applications, Journal of Energy Storage 84 (2024) 110867. **Impact factor: 9.4, CiteScore: 10.3.** **6.** M. Bora, S. Mohanty, Anil K. Singh, Weibo Gao and P. Deb, Adaptive Half-metallicity via magnetic proximity in an electrically sensitive 1T'-$WTe_2/CrBr_3$ vdW heterostructure. Accepted in Applied Surface Science (2023). **Impact factor: 7.392, CiteScore: 12.1.** **7.** M. Pershaanaa, Fathiah Kamarulazam, Ong Gerard, Z.L. Goh, Shahid Basir, Kashmiri Baruah, Pritam Deb, S. Ramesh, K. Ramesh, MXenes and their transformation to composites for potential applications. Materials Today Communications 35(2023) 106143. **Impact factor: 3.662, CiteScore: 3.4.** **8.** H. Pan, C. Zhang, J. Shi, X. Hu, N. Wang, L. An, R. Duan, P. Deb, Z. Liu, W. Gao, Room-Temperature Lateral Spin Valve in Graphene/Fe3GaTe2 van der Waals Heterostructures. ACS Materials Letters 5 (2023) 2226–2232. **Impact factor: 11.4, CiteScore: 13.6**. **9.** L. Gogoi, W. Gao, P. M. Ajayan, and P. Deb, Quantum Magnetic Phenomena in Engineered Heterointerface of Low Dimensional van der Waals and non-van der Waals Materials. Physical Chemistry Chemical Physics 25 (3) (2023) 1430-1456. **Impact factor: 3.945, CiteScore: 6.3.** **10.** K. Konwar, N. Sharma, P. Pranjali, A. Guleria, S. D. Kaushik, A. Dutta, R. Mukhopadhyay, D. Sen, W. Gao, and P. Deb, Structure-Correlated Magnetic Resonance Transverse Relaxivity Enhancement in Superparamagnetic Ensembles with Complex Anisotropy Landscape. Langmuir 38(2022) 11087–11098. **Impact factor: 4.331, CiteScore: 6.7.** **11.** Monika Sharma, Anil Kumar Singh, M. Pershaanaaa, Ramesh Kasi, Ramesh Subramaniam, Pritam Deb, 2D based Hybrid nanostructure as an advanced electrode material for High-Performance Supercapacitor application. (**Communicated**) **12.** Anil Kumar Singh, Pritam Deb, Stacking independent robust thermoelectric behavior in magnetically coupled $CrBr_3/NbSe_2/CrBr_3$ vdW heterostructure, conference proceedings. **(Communicated)**
Technology/ New Processes/ Patents generated	NA
Scope for commercializing the new Scientific Knowledge	NA

10. Please elaborate with your remarks on the collaboration:

The ASEAN project provides us the opportunity to collaborate with research group from different ASEAN countries (Singapore & Malaysia), which offers a multitude of advantages, including access to expertise, equipment & computational facilities, data, advanced technologies, networking opportunities, and avenues for dissemination. By leveraging these collaborative advantages, we are able enhance the quality, impact, and relevance of our research endeavors. The access to sophisticated equipment and computational facilities through collaboration reduce the costs and expand the scope of our research activities. This also facilitates the exchange of data, samples, and resources, which enables us to validate the robustness and reliability of our research findings. Moreover, our collaborating groups at the forefront of technological

advancements provide exposure to cutting-edge technologies, which helps us to conduct highly controlled experimental techniques, enhancing the efficiency and accuracy of the research outcomes. The collaboration between these three research groups fosters networking opportunities and potential future collaborations, which stimulates interdisciplinary collaborations that can lead to novel insights and discoveries. Nonetheless, the outcomes of our joint research venture presented in 67th DAE-SSPS national conference 2023, which allows us to disseminate the research findings to a wider audience and establish connections with other researchers and potential collaborators.

The Collaboration with research groups from Singapore and Malaysia brings together a diverse range of expertise with specialized knowledge. By pooling expertise, our collaboration efficiently deals with the proposed complex research problems, leading to more innovative and insightful research outcomes.

11. Application potential (immediate/long term)-

The findings of our proposed research work show potential application in various domains such as energy storage, energy conversion, Magnetic resonance imaging (MRI), spintronic devices etc. This leads to the new cutting-edge technologies along with advancement of the existing technologies. Moreover, the developed low-dimensional materials offer uno-numero platform to realize enhanced mechanical, physical, thermal, chemical properties etc. In this regard, the presence of both EDLC and pseudocapacitive component makes the developed systems a potential supercapacitive electrode, which acts as a bifunctional electroactive material for methanol catalysis and high-performance quasi-solid state symmetric supercapacitor. On the other hand, the enhancement in transverse MR-contrast efficacy in the developed contrast probe offers exceptional platform to realize dual mode MR imaging. Further, the fabricated and modelled spin valve devices possess large tunable tunnelling magnetoresistance, which makes it a suitable candidate to design room temperature memory devices such as magnetic random-access memory (MRAM).

12. Financial details of the project-

Total project cost	Rs. 32,52,496
Money received	Rs. 16,26,248
Expenditure incurred	Rs. 16,08,174
Final SE/UC (in prescribed format attached	

13. Conclusion summarizing the achievements and indication of scope for future work-

It is worthwhile to mention that, we have realized strong magnetic proximity effect in low-dimensional materials as proposed in the approved objectives. In this regard, we have engineered 2D nanocomposites, hybrid heterostructures, vdW heterostructures and conduct various characterizations to validate their practical applicability. The findings of our research work suggest potential application of the developed systems in the field of energy storage, energy conversion, Magnetic resonance imaging (MRI), spintronic devices etc. Such multifunctionality of the fabricated quantum materials leads to the new cutting-edge technologies and advancement of the existing technologies. Nonetheless, the joint-research work carried out under this project leads to the publications of Eight (8) papers in peer reviewed international journals and four (4) papers are under communication with proper acknowledgement. Also, this joint scientific research work fosters networking opportunities and potential future collaborations, which stimulates interdisciplinary collaborations that can lead to novel insights and discoveries.

Annexure-II

REQUEST FOR ANNUAL INSTALMENT WITH UP-TO-DATE STATEMENT OF EXPENDITURE

1. SERB Sanction Order No and date : CRD/2020/000197 and 02/09/2021
2. Name of the PI : Prof. Pritam Deb
3. Total Project Cost : 32,52,496
4. Revised Project Cost (if applicable) : 32,52,496
5. Date of Commencement : 16/09/2021
6. Statement of Expenditure :
   (Month wise expenditure incurred during current financial year)

Month & year	Expenditure incurred/ committed
MARCH/2023	**31,000**
APRIL/2023	**37,000**
MAY/2023	**37,000**
JUNE/2023	**37,000**
JULY/2023	**37,000**
AUGUST/2023	**37,000**
SEPTEMBER/15/09/2023	**38,351** [18,500 (fellowship amount till 15th September) +1,851 (consumables) +18,000 (arrear amount of for the months of January, February and March 2023.)]

1. Grant received in each year:
   a. 1st Year : 16,26,248
   b. 2nd Year :
   c. 3rd Year :
   d. Interest, if any : 20,538
   e. Total (a + b + c + d) : 16,46,786

Statement of Expenditure

(to be submitted financial year wise i.e. 16/09/2021 to 31/03/2022, 01/04/2022 to 31/03/2023 and 01/04/2023 to 15/09/2023

Sr No (I)	Sanctioned Heads (II)	Total Funds Allocated (indicate sanctioned or revised (III)	Expenditure Incurred			Total Expenditure till 15/09/2023 (VII = IV + V + VI)	Balanceas on (15/09/2023) (VIII =III – VII)	Requirement of Fundsupto 15/09/2023	Remarks (if any)
			1st Year (16/09/2021 to 31st March 2022) (IV)	2 Year (1st April 2022 to 31st March 2023) (V)	3rd Year & so on (1st April to 15/09/2023) (VI)				
1.	Manpower costs	8,03,520	93,000	3,72,000	2,52,500	7,17,500	86,020	0	
2.	Consumables	2,56,000	Nil	1,85,149	1,851	1,87,000	69,000	0	
3.	Travel	21,40,000	Nil	6,77,186		6,77,186	14,62,814	0	
4.	Contingencies	0						0	
5.	Others, if any	0						0	
6.	Equipment	0						0	
7.	Overhead expenses	52,976	16,555	9,933		26,488	0	0	
8.	Total	**32,52,496**	**1,09,555**	**12,44,268**	**2,54,351**	**16,08,174**	**16,44,322**	**0**	

***Including interest, the closing balance sums up to (16,44,322+20,538) = 16,64,860/-**

Name and Signature of Principal Investigator:

Dr. P. Deb
Professor
Dept. of Physics
Tezpur University, Tezpur-784028

Date: 14/06/2024

Signature of Competent financial authority: _____
(with seal) Date: _____

Finance Officer
Tezpur University

*** DOS – Date of Start of project**

Note:

1. Expenditure under the sanctioned heads, at any point of time, should not exceed funds allocated under that head, without prior approval of SERB i.e. Figures in Column (VIII) should not exceed corresponding figures in Column (III)
2. Utilization Certificate (Annexure III) for each financial year ending 31st March has to be enclosed along with request for carry-forward permission to the next financial year.

GFR 12 – A

UTILIZATION CERTIFICATE (UC) FOR THE YEAR 01/04/2023 to 15/09/2023
in respect of RECURRING
as on 31/03/2023 to be submitted to SERB

Is the UC.....*(Provisional/Audited)*

(To be given separately for each financial year ending on 31st March)

1. Name of the grant receiving Organization: Tezpur University
2. Name of Principal Investigator (PI): Prof. Pritam Deb
3. SERB Sanction order no. & date: CRD/2020/000197 & 02/09/2021
4. Title of the Project: Realizing proximity effect in superconductor/semiconductor-ferromagnet van der Waals heterostructure.
5. Name of the Scheme: ASEAN-India Science & Technology Development Fund (AISTDF)
6. Whether recurring or non-recurring grants: Recurring
7. Grants position of the beginning of the financial year
   - i) Carry forward from previous financial year: **2,92,963**
   - ii) Others, if any: Nil
   - iii) Total: **2,92,963**
8. Details of grants received, expenditure incurred and closing balances: (Actuals)

Unspent Balance of Grants received previous years	Interest Earned thereon	Interest deposited back to the SERB	Grant received during the year			Total available funds (1+2+3+4)	Expenditure Incurred	Closing Balances (5-6)
1	2	3	4			5	6	7
			Sanction no. (i)	Date (ii)	Amount (iii)			
2,92,963	NIL	NIL	CRD/2020/000197	16/09/2021	NIL	**2,92,963**	**2,54,351**	**38,612**

Component wise utilization of grants:

Grant-in-aid-General
2,54,351

Details of grants position at the end of the year

(i) Balance available at end of financial year = **38,612**

(ii) Unspent balance refunded to SERB (If any) = NIL

(iii) Balance (Carried forward to next financial year) if applicable = **38,612**

Dr. P. Deb
Professor
Dept. of Physics
Tezpur University, Tezpur-784028

GFR 12 – A

UTILIZATION CERTIFICATE (UC) FOR THE YEAR 01/04/2023 to 15/09/2023
in respect of RECURRING
as on 15/09/2023 to be submitted to SERB

Is the UC.....*(Provisional/Audited)*

(To be given separately for each financial year ending on 31st March)

Certified that I have satisfied myself that the conditions on which grants were sanctioned have been duly fulfilled/are being fulfilled and that I have exercised following checks to see that the money has been actually utilized for the purpose which it was sanctioned:

i. The main accounts and other subsidiary accounts and registers (including assets registers) are maintained as prescribed in the relevant Act/Rules/Standing instructions (mention the act/Rules) and have been duly audited by designated auditors. The figures depicted above tally with the audited figures mentioned in financial statements/accounts.

ii. There exist internal controls for safeguarding public funds/assets, watching outcomes and achievements of physical targets against the financial inputs, ensuring quality in asset creation etc. & the periodic evaluation of internal controls is exercised to ensure their effectiveness.

iii. To the best of our knowledge and belief, no transactions have been entered that are in violation of relevant Act/Rules/standing instructions and scheme guidelines.

iv. The responsibilities among the key functionaries for execution of the scheme have been assigned in clear terms and are not general in nature.

v. The benefits were extended to the intended beneficiaries and only such areas/districts were covered where the scheme was intended to operate.

vi. The expenditure on various components of the scheme was in the proportions authorized as per the scheme guidelines and terms and conditions of the grants-in-aid.

vii. It has been ensured that the physical and financial performance under AISTDF (name of the scheme) has been according to the requirements, as prescribed in the guidelines issued by Govt. of India and the performance/targets achieved statement for the year to which the utilization of the fund resulted in outcomes given at Annexure-I duly enclosed.

viii. The utilization of the fund resulted in outcomes given at Annexure-II duly enclosed (to be formulated by the Ministry/Department concerned as per their requirements/specifications)

ix. Details of various schemes executed by the agency through grants-in-aid received from the same Ministry or from other Ministries is enclosed at Annexure-II(to be formulated by the Ministry/Department concerned as per their requirements/specifications)

Date: 24/06/2024
Place: Tezpur University

Dr. P. Deb Professor Dept. of Physics Tezpur University, Tezpur-784028 **Signature of PI:**	24/6/24 Finance Officer Tezpur University **Signature with Seal:** **Name:** **Chief Finance Officer(Head of Finance)**	24/6/24 Registrar Tezpur University **Signature with Seal:** **Name:** **Head of Organisation**