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Establishing the Quantum-Engineered Nano Devices Laboratory (QENDL) at NIWC Pacific

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EXECUTIVE SUMMARY

This technical document summarizes the recently established and novel capabilities offered by the Quantum-Engineered Nano Devices Laboratory (QENDL) in Code 55360, Advanced Photonic Technologies Branch, Topside Complex, NIWC Pacific, San Diego, CA. Dr. Torres, Jr. served as the principal investigator in the FY18 Naval Innovative Science and Engineering (NISE) Laboratory Recapitalization funded effort to establish the necessary in-house capabilities for fundamental studies, and test and evaluation of novel devices in the area of quantum and nanotechnology.

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ACRONYMS

2D	two-dimensional
C5ISR	Command, Control, Computers, Communications, Cyber, Intelligence, Surveillance, and Reconnaissance
CCR	closed cycle refrigerator
CVT	continuously variable temperature
DC	direct current
DON	Department of the Navy
EMW	Electromagnetic Maneuver Warfare
FY	fiscal year
K	Kelvin
NISE	Naval Innovative Science and Engineering
NIWC	Naval Information Warfare Center
ONR	Office of Naval Research
PI	principal investigator
PL	photoluminescence
QENDL	Quantum-Engineered Nano Devices Laboratory
T	Tesla

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1. INTRODUCTION

1.1 PURPOSE

The conceptual vision of the operational battlespace of 2045 in the 2017 Department of the Navy (DON)'s 30 Year Research and Development Plan predicts quantum-based sensing, nanotechnology, and photonics as Key Programs and Technology Investments [1]. The DON identifies advanced materials and manufacturing technologies and advanced computing and sensing as core technology areas that must be built and sustained. Furthermore, the Electromagnetic Maneuver Warfare (EMW) focus area in the 2015 Office of Naval Research (ONR) Naval Science and Technology Strategy seeks to "enable the warfighter to have complete control over the electromagnetic spectrum…" [2]. For these reasons, NIWC Pacific invested via an FY18 Naval Innovative Science and Engineering (NISE) Laboratory Recapitalization effort in establishing a novel laboratory—the Quantum-Engineered Nano Devices Laboratory (QENDL)—that emphasizes various modalities of characterization of advanced materials and devices. QENDL's mission is to explore and exploit the exotic properties of atomic-layered, two-dimensional (2D) materials, quantum materials, and their heterostructures for the benefit of the future warfighter in terms of Command, Control, Computers, Communications, Cyber, Intelligence, Surveillance, and Reconnaissance (C5ISR), EMW, and spectrum dominance.

1.1.1 Brief Overview of QENDL

A brief overview of the various equipment and capabilities offered by QENDL follows. Figure 1 presents a visual overview of the QENDL facility.

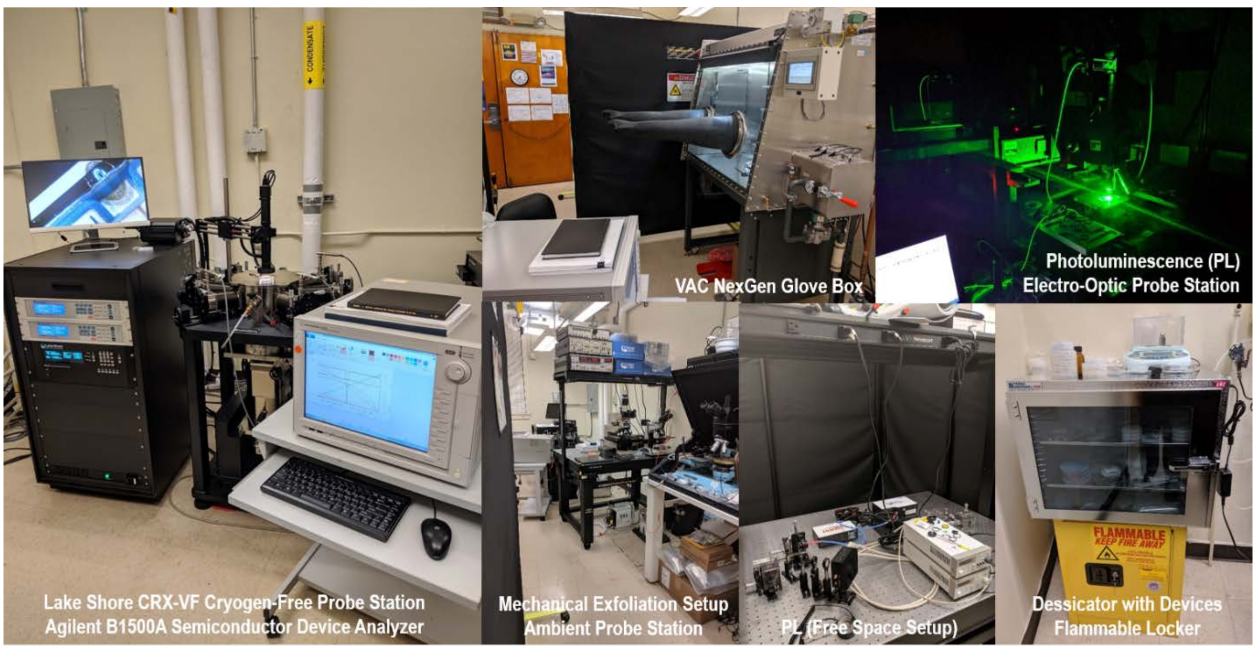

Figure 1. Overview of QENDL.

QENDL features several capabilities for the electrical and optical characterization of nanomaterials and nanodevices. QENDL features a Lake Shore CRX-VF cryogen-free probe station for the rapid prototyping and characterization of devices via an Agilent B1500A Semiconductor Device Analyzer, a Vacuum Atmospheres Company (VAC) NexGen glove box for the processing and synthesis of ionic liquids and ion-gels, a custom-made electro-optic probe station for photoluminescence and Raman spectroscopy, a mechanical exfoliation and dry transfer setup towards the development of flake-based van der Waals heterostructure devices, an ambient probe station, a free space photoluminescence setup, an MMR Technologies elan2 digital liquid nitrogen generator autotransfer station, and a Terra Universal SMART desiccator for sample and device storage.

Figure 2 shows another view of the QENDL facility. From left to right (top panel): Terra Universal SMART desiccator on top of a flammable storage locker; Lake Shore CRX-VF cryogen-free probe station with the Agilent B1500A Semiconductor Device Analyzer; custom-made electro-optic probe station for PL and Raman spectroscopy; MMR Technologies elan2 digital liquid nitrogen generator autotransfer station with dewars. From left to right (bottom panel): mechanical exfoliation and dry transfer setup for preparation of flake-based van der Waals heterostructures, VAC NexGen glove box, 2D material-based devices (semiconductor chip) loaded into the Lake Shore CRX-VF probe station with four direct current (DC) probe arms and two fiber optic probe arms in their vicinity, and an ambient probe station.

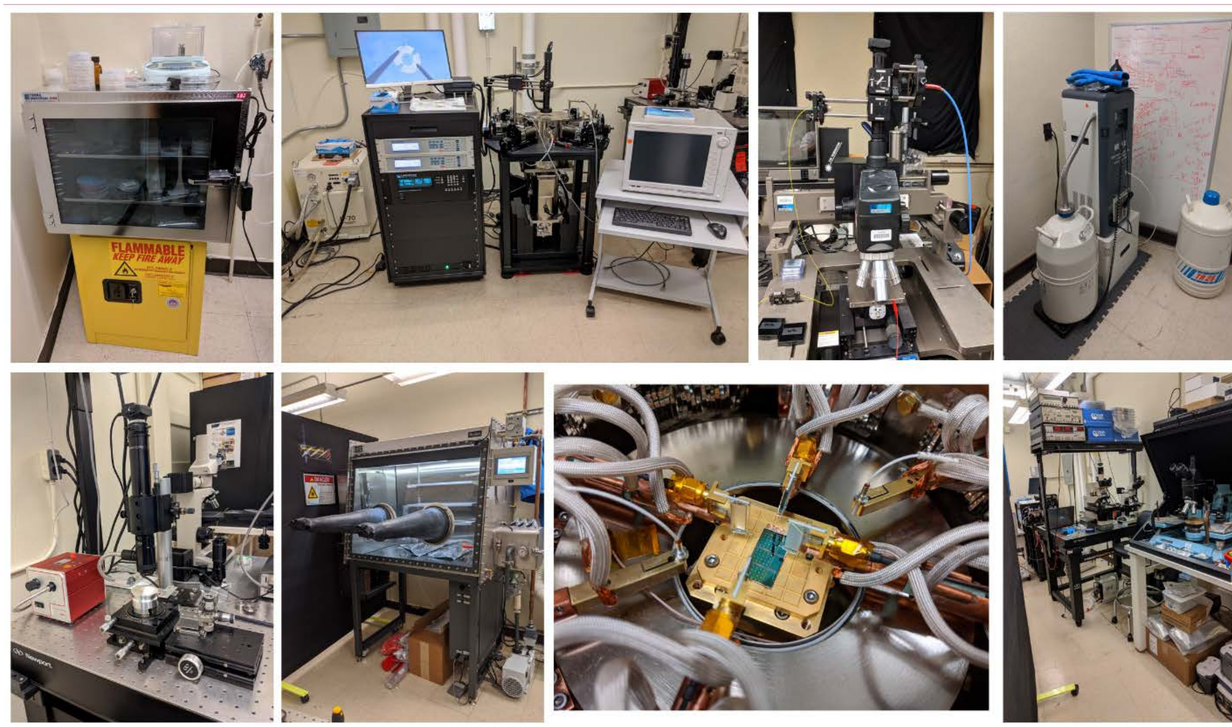

Figure 2. Lab Tour of QENDL at NIWC Pacific, San Diego, California as of February 2020.

Figure 3 highlights the device fabrication and device characterization, which are performed at the UCSD Nano3 cleanroom facility and QENDL at NIWC Pacific, respectively.

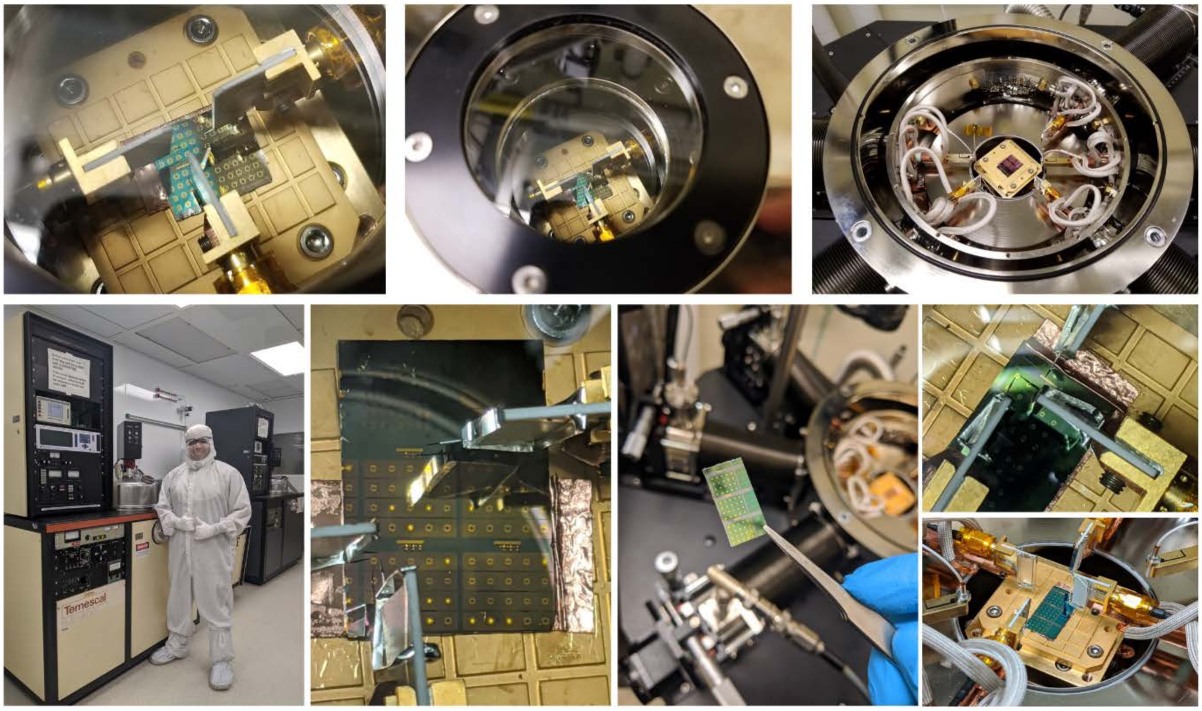

Figure 3. Device Fabrication and Characterization.

Device fabrication is performed by the principal investigator (PI) utilizing an Indefinite Delivery/Indefinite Quantity (IDIQ) Task Order at the University of California, San Diego (UCSD) Nano3 Class 1000 cleanroom facility. The devices are then electrically and optically characterized in-house via the cryogen-free probe station and photoluminescence setup in QENDL at NIWC Pacific. The images in Figure 3 show several 2D material-based devices being loaded into the cryogen-free probe station. The bottom left image shows the PI in the UCSD Nano3 cleanroom facility during metal evaporation using a Temescal BJD 1800 e-beam evaporator. The bottom right image shows the four DC probe arms and two fiber optic probe arms inside the probe station.

1.2 SPECIFICATIONS OF THE MAIN EQUIPMENT IN QENDL

The Lake Shore CRX-VF cryogen-free probe station features a closed cycle refrigerator (CCR) operating in the Gifford-McMahon refrigerator cycle, allowing for unsupervised cool-down and convenience during measurements. It features four DC probe arms for electrical measurements with either Tungsten (W) or Berylium Copper (BeCu) probe tips. The probe tips can be either standard or continuously variable temperature (CVT) tips so that one does not need to move the tips during temperature cycling. The system also features two fiber optic probe arms using a standard normally incident fiber holder for photoexcitation/detection as well as a novel 3D printed fiber holder option for tilted photoexcitation/detection. The base temperature can reach down to 5.7K and the system can be heated up to 500K. The system also features a vertical field superconducting magnet up to +/-2.5T from base temperature (5.7K) to 10K, +/-2T from 11K – 400K, and +/-1T from 401K – 500K. A cryogen-free probe station enables the characterization of electric, magnetic, and optical properties of advanced materials and novel nano-devices for next generation warfighter technology.

Figure 4 summarizes the current options and specifications for our Lake Shore CRX-VF probe station.

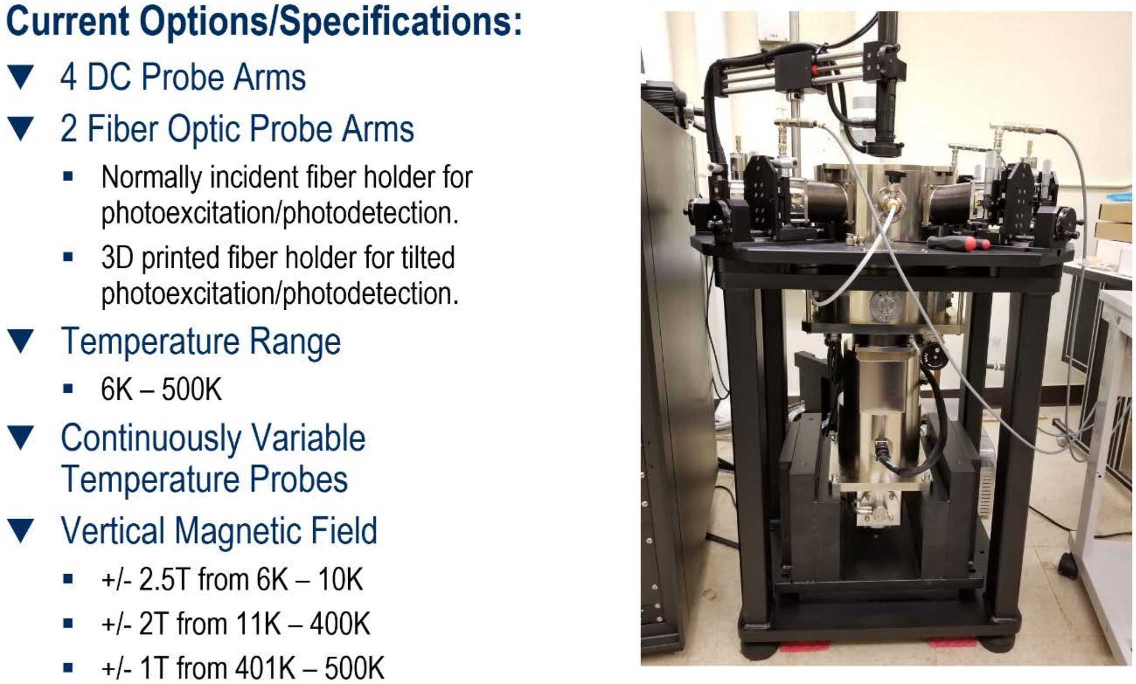

Figure 4. Current Options and Specifications for our Lake Shore CRX-VF Probe Station.

The Vacuum Atmospheres Company (VAC) NexGen Glovebox System with Inert Gas Purification features replaceable and independent oxygen and moisture cartridge-based inert gas purifiers with dedicated blowers. This feature eliminates the need for regeneration, which results in less downtime compared to standard gloveboxes. The oxygen and moisture levels can reach down to less than 1 part per million (ppm) oxygen and moisture in the glove box. The glove box also features a panel with four Bayonet Neill–Concelman (BNC) electrical sockets for sensitive device electrical biasing in an inert environment. The glove box also features a dedicated freezer that can reach down to -35^{o}C for sample/chemical storage. A state-of-the-art glove box enables investigation of novel materials (e.g., high-quality ion-gels, energy harvesting materials, quantum dots, etc.) that are oxygen and moisture sensitive and can be exploited in various nano-device architectures.

Figure 5 summarizes the current options and specifications for our VAC NexGen glove box.

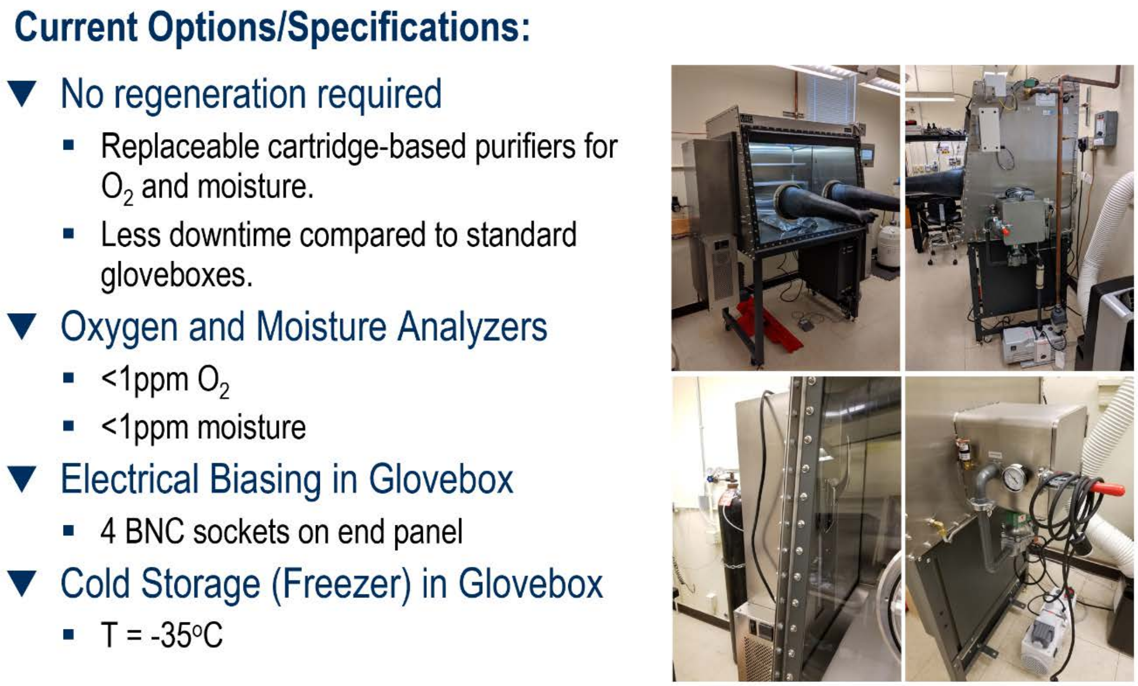

Figure 5. Current Options and Specifications for our VAC NexGen Glove Box.

1.3 FUTURE CAPABILITIES

The QENDL Lab (Phase 1) is fully operational with a cryogenic probe station (device characterization under various magnetic fields, electric fields, temperature, and photoexcitation via optical fibers) and glove box (<1ppm O_2/H_2O) for ion-gel synthesis. However, we are unable to perform basic quantum optics experiments that would allow us to research various promising material systems towards quantum-based nanotechnologies (e.g., quantum light sources) for future quantum computing applications. In the future, we plan to augment QENDL to feature state-of-the-art equipment to study quantum nanophotonics of various material systems (e.g., quantum dots, 2D quantum materials, 2D quantum material heterostructures, silicon nitride based platforms, superconducting quantum interference devices (SQUIDs, etc.) with potential applications in future hybrid integrated quantum photonic circuits and on-chip quantum computing with 2D materials.

The following equipment will be essential to perform these experiments:

1. FastHall Effect Measurement Controller for Lake Shore CRX-VF cryogen-free probe station
2. RF/microwave probe arms for Lake Shore CRX-VF cryogen-free probe station
3. Time-correlated single photon counter (TCSPC)
4. Single photon detectors
5. High resolution spectrometer
6. Cryogen-cooled imaging charge-coupled device (CCD) cameras from the ultraviolet to the short-wave infrared (UV-SWIR)

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2. CONCLUSIONS

This technical document presented an overview of NIWC Pacific's new, fully functional, Quantum-Engineered Nano Devices Laboratory (QENDL). NIWC Pacific funded the first phase of QENDL via an FY18 NISE Laboratory Recapitalization effort (Section 219 funds). QENDL's mission is to explore and exploit the exotic properties of atomic-layered, 2D materials, quantum materials, and their heterostructures for the benefit of the future warfighter in terms of C5ISR, EMW, and spectrum dominance.

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REFERENCES

1. U.S. Department of the Navy, Research, Development, Test & Evaluation [2017] Washington, D.C.: 30 Year Research & Development Plan.
2. Office of Naval Research [2015] Arlington, Virginia: Naval S&T Strategy.

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14. ABSTRACT

This technical document summarizes the recently established and novel capabilities offered by the Quantum-Engineered Nano Devices Laboratory (QENDL) in Code 55360, Advanced Photonic Technologies Branch, Topside Complex, NIWC Pacific, San Diego, CA. Dr. Torres, Jr. served as the principal investigator in the FY18 Naval Innovative Science and Engineering (NISE) Laboratory Recapitalization funded effort to establish the necessary in-house capabilities for fundamental studies, and test and evaluation of novel devices in the area of quantum and nanotechnology.

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