PROJECT DESCRIPTION

The goal of the proposed research is to develop novel quantum dot nanomaterials that emit entangled photons, enabling transformative technologies such as quantum cryptography. Integrated outreach targets Idaho elementary education to increase diversity in science, technology, engineering and math (STEM).

INTRODUCTION AND SIGNIFICANCE

Quantum information technologies promise to revolutionize society. Imagine using your home computer to solve complex problems now considered intractable, and then making an online purchase with zero risk of your personal information falling into a hacker's hands. By exploiting the unusual predictions of quantum mechanics, massively parallel quantum computers will one day perform with unprecedented computational power, while quantum encryption will permit unbreakably secure communication to mitigate serious and increasingly common data breaches. Many strategies for realizing these world-changing ideas rely on the quantum entanglement of photons,[1–4] often generated using semiconductor ***quantum dots (QDs)***.[5–7] Unfortunately, traditional QDs are inefficient entangled photon emitters.[8] In contrast, a new class of QD nanomaterials I have recently developed is much better suited to this task, due to their highly symmetric structure.[9, 10] The preliminary experimental results I present here indicate that these novel QDs will help satisfy the urgent need for efficient entangled photon sources.[11–13]

In the research plan, I propose to develop these novel QDs into robust entangled photon sources, with an eye towards their eventual use in scalable, on demand entangled photon devices. This unique, potentially transformative work will advance materials science by aligning with EPM research objectives, including: self-assembly; low-dimensional materials; synthesis-structure-property relationships; nanostructure nucleation and growth at atomic levels; and novel material integration for advanced optoelectronics. The proposed research also overlaps with EPMD's interest in single photon and quantum devices.

In the education and outreach plan, I propose activities designed to positively impact STEM education, to provide undergraduates with service-learning opportunities, and ultimately to increase STEM workforce diversity in Idaho. As more of our daily activities are carried out online, public interest in data security has grown. STEM activities will hence focus on quantum cryptography, integrating the outreach with the research, and extending the impact of both. Effective outcomes demand participation and ongoing support from key stakeholders, so program components target different elementary school audiences: **(1)** students, particularly females and other underrepresented groups; **(2)** teachers; and **(3)** communities and families.

I will also use this proposal to describe how, taken together, the research, education and outreach plans align with my ongoing professional goals. Successfully establishing these programs during this five-year project will help me launch a highly productive and sustainable career addressing cutting-edge research.

RESEARCH PLAN

RESEARCH GOAL AND OBJECTIVES

To meet the goal of developing QDs for entangled photon emission, I will complete the objectives below:

1. ***Define tensile-strained quantum dot (TSQD) synthesis-structure-property relations***—develop a comprehensive understanding of these new low-dimensional nanomaterials via systematic study.
2. ***Explore TSQD nucleation and growth at atomic levels*** —use island scaling theory to probe TSQD self-assembly; accelerate island scaling experiments with predictions from computational modeling.
3. ***Demonstrate photon entanglement in TSQDs***—use feedback from experiment and models to fine-tune TSQD synthesis for optimized emission; measure quantum optical properties of TSQDs.
4. ***Investigate fiber-compatible entangled photon emission***—create TSQDs from smaller band gap materials to increase wavelength of entangled photons towards 1.3 or 1.55 μm.
5. ***Fabricate proof-of-concept devices***—build light-emitting TSQD devices for on demand entangled photon generation; show this novel method of material integration enables scalable optoelectronics.

BACKGROUND

The development of a robust, scalable method for generating entangled photons will mark a critical milestone on the road to quantum information technologies becoming part of our daily lives.[1–5] According to quantum mechanics, to *entangle* a pair of photons is to cause them to interact in such a way that even if some arbitrarily large distance separates them, their polarizations remain linked. Entanglement is achieved by simultaneously creating a pair of photons that both exhibit a *superposition* of all polarization states. Subsequently measuring one of the photons to discover its polarization instantaneously causes its pair to assume the opposite polarization.

Research groups have explored various means to create these entangled photon pairs. Methods used include electron-hole recombination in III-V semiconductor QDs,[6, 7] and various non-linear optical effects.[14–17] QD-based approaches offer some distinct advantages. QDs are compact, tunable, and we can electrically trigger them to emit photons on demand, which is critical for future devices.[18–20] We can easily integrate QDs into complex planar architectures that are compatible with high-volume semiconductor processing lines, something not possible with the bulky non-linear approaches.[21, 22]

The generation of polarization-entangled photons inside QDs relies on the biexciton-exciton cascade (***Fig. 1***). A biexciton (two bound electron-hole pairs, $|XX\rangle$) is created using a pump laser. The biexciton decays into one of two intermediate exciton states (one bound electron-hole pair, $|X_V\rangle$ or $|X_H\rangle$) by emitting an XX photon (blue/top half in ***Fig. 1***). The populated exciton state then decays into the ground state, $|0\rangle$, emitting an X photon (red/bottom half in ***Fig. 1***). The difference in energy between the two intermediate exciton states, |s|, is known as the ***fine-structure splitting (FSS)***. If |s| is larger than the radiative linewidths, ΔE, of the emitted photons, then the decay path the electron took is distinguishable and the polarizations of the emitted photons are classically correlated (***Fig. 1(a)***). However, if |s| is reduced almost to zero then the two decay paths are indistinguishable, and the XX and X photons emitted will be polarization entangled (***Fig. 1(b)***).

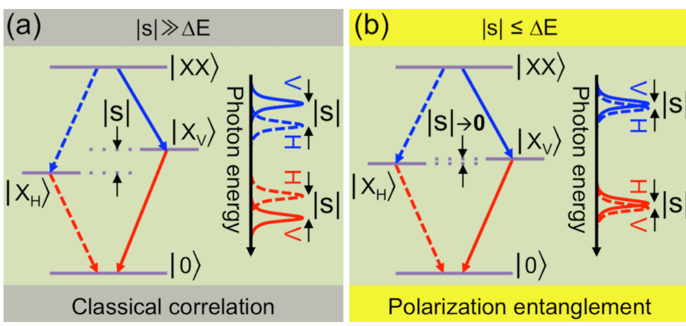

Fig. 1: Biexciton-exciton cascades with corresponding ***photoluminescence (PL)*** spectra. (a) For large |s|, the two decay paths are distinguishable, leading to classically correlated photon polarizations. (b) As |s|→0 the two paths are indistinguishable and emitted photons are polarization entangled (after [24]).

Despite their attractive attributes listed above, traditional QDs have large FSS and so are not well suited to generating entangled photon pairs.[8, 23, 24] Traditional QDs self-assemble under compressive strain on (001)-oriented substrates. The (001) surface lends QDs an asymmetric shape and an in-plane piezoelectric field, causing large FSS.[8, 11] Overcoming this large FSS requires painstaking post-growth QD selection and manipulation, which would be a problem for high-throughput production.[7, 23, 25, 26] A more sophisticated and scalable approach would be to grow QDs with inherently small FSS. If every QD in a sample could generate entangled photons, these time-consuming steps would be unnecessary.

FSS is predicted to be vanishingly small in QDs grown on (111) surfaces.[11, 12] The challenge for materials science is that in the past, (111) QDs have been almost impossible to grow without defects that destroy their ability to emit light. Traditional compressive (001) QDs (e.g., InAs on GaAs) do not form on (111) surfaces.[27] To get around this problem, researchers have tried growing (111) QDs by droplet epitaxy, or on pre-patterned (111) substrates.[28–31] These methods show signs of success,[28, 32, 33] but both have drawbacks. Droplet epitaxy requires low growth temperatures that cause arsenic-related defects.[34, 35] Patterned substrate growth results in non-planar devices that complicate sample processing, and hinder QD placement into photonic cavities for efficient photon extraction.[33, 36]

Preliminary Research Results and Relevant Expertise

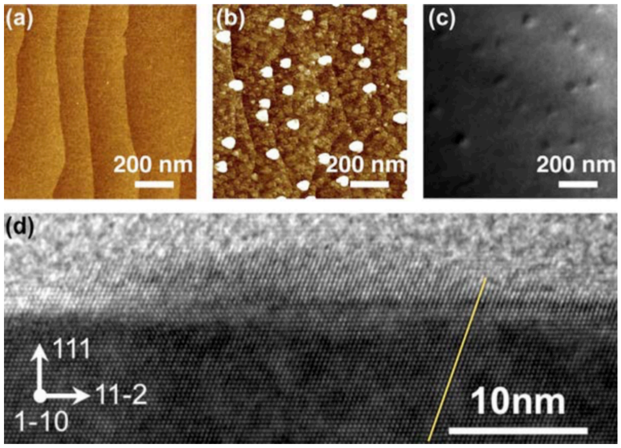

Fig. 2: GaAs(111)A surface (a) before and (b) after GaP TSQD growth. (c) Plan-view, and (d) cross-section microscopy confirms TSQDs are dislocation-free.[9]

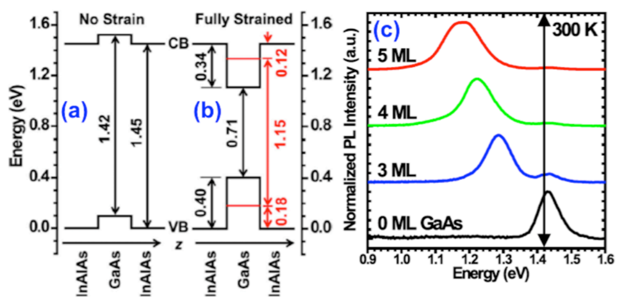

Fig. 3: Calculated band structures for (a) unstrained, and (b) tensile-strained GaAs/InAlAs(111) at 300 K. In (b), tensile strain lowers the GaAs band gap inducing type-I quantum confinement. (c) PL spectra showing emission is tunable with GaAs TSQD size below the band gap of bulk GaAs (arrow at 1.42 eV).[13, 38]

I wanted to find a simpler way to create low FSS QDs that avoids these drawbacks. I recently revisited the materials challenge of strain-driven QD self-assembly on (111) surfaces. In doing so, I have pioneered a novel method for growing (111) QDs by molecular beam epitaxy (MBE).

I discovered that by harnessing *tensile instead of compressive strain* we can create self-assembled QDs on (111) surfaces (***Figs. 2(a)–(b)***).[9, 10, 37] These ***tensile-strained QDs (TSQDs)*** form spontaneously during MBE growth. The specific combination of a (111) surface and tensile strain,[10] means that (111) TSQDs grow without the defects plaguing compressive (111) QDs (***Figs. 2(c)–(d)***). As a result, TSQDs are optically active at room temperature. We can tune photon energy by controlling TSQD size (***Fig. 3***).[13, 38, 39]

GaAs/InAlAs(111) TSQDs form under 3.8% tensile strain. Tensile strain reduces semiconductor band gaps, which has two benefits. First, it increases carrier confinement in the GaAs TSQDs, for higher temperature operation (***Figs. 3(a)–(b)***). Second, TSQD light emission is *lower* in energy than from bulk, unstrained GaAs (***Fig. 3(c)***).[13, 38, 39] This second behavior is very unusual. Traditional QDs emit light at very much *higher* photon energy than their unstrained semiconductor constituents due to the compressive strain. For example, at 300K, compressive InAs/GaAs(001) QDs typically emit light at photon energies 0.95–1.3 eV, compared to bulk InAs at 0.35 eV. In contrast, GaAs(111) TSQDs emit light at photon energies 1.18–1.28 eV, i.e. *lower* than bulk GaAs at 1.42 eV (***Fig. 3(c)***).[13] This ability of TSQDs to push photon energy in the opposite direction represents a new tool for nanomaterials design.

Most significantly for this project, preliminary results show that GaAs TSQDs on (111) surfaces exhibit very low FSS (***Fig. 4***).[13] As predicted, high-resolution micro-PL shows FSS from several individual TSQDs of 2–26 μeV—significantly lower than in traditional (001) QDs,[6, 23, 25, 26] and comparable to (111)-oriented QDs grown using the complex techniques above.[28, 29, 32, 33] This previously overlooked strategy of tensile-strained self-assembly creates (111) QDs with very low FSS, and presents us with an unrivaled opportunity to develop robust and truly scalable entangled photon emitters.

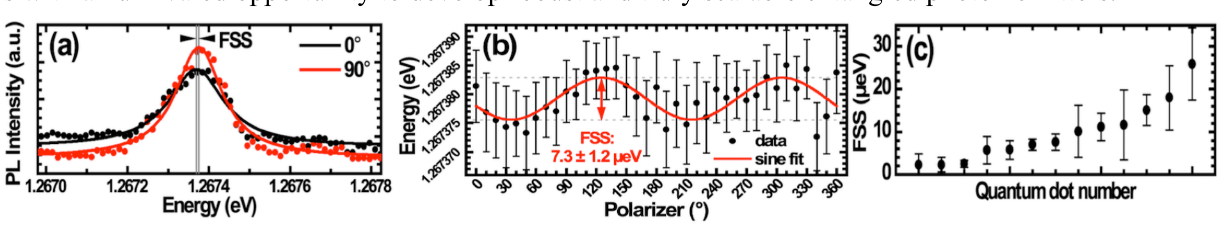

Fig. 4: (a) Polarization-resolved μ-PL of a GaAs(111) TSQD at 9 K. (b) Peak position in (a) shifts with angle of polarization due to FSS: fitting reveals FSS = 7.3 ± 1.2 μeV. (c) FSS in 13 individual TSQDs on this sample.[13]

RESEARCH PLAN METHODOLOGY

On the strength of these highly encouraging preliminary results, I propose a comprehensive study of the growth and characteristics of TSQD nanomaterials based on III-V semiconductors for quantum optics applications. I will create TSQDs with properties tailored towards proof-of-concept entangled photon emitters, and demonstrate to the wider materials science community the enormous potential of tensile-strained self-assembly for novel nanomaterial synthesis and integration. To meet this goal, I will complete the five objectives on page 1 of the Project Description, using the research methodologies below.

OBJECTIVE 1: DEFINE TSQD SYNTHESIS-STRUCTURE-PROPERTY RELATIONS

Completing this objective will enable my research team to control TSQD structure, strain and optical response using MBE growth parameters. We will learn to reproducibly synthesize defect-free TSQDs with properties engineered for subsequent components of the research program. GaAs/InAlAs(111) TSQDs are still so new that many of their fundamental materials characteristics are not yet fully known. We will systematically study the effect of MBE growth conditions on TSQD morphology, areal density, and optical behavior.

TSQD morphology, structure, areal density. The main control parameters during MBE growth of III-V semiconductors are the substrate temperature, growth rate, and V/III ratio. During initial studies of a similar TSQD system (GaP/GaAs) I found that raising substrate temperature controllably increases TSQD size (***Fig. 5***), while lowering growth rate reduces areal density.[9, 10] This response is also what we would expect when growing traditional QDs, suggesting that tensile and compressive self-assembly are kinetically similar. This is a key result: it means we can borrow from the wealth of knowledge already established for traditional QDs.

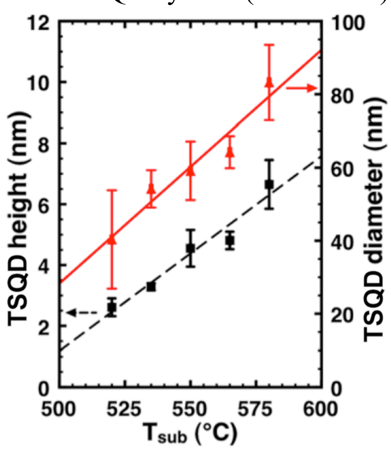

Fig. 5: Control of self-assembled GaP/GaAs(111)A TSQD size using substrate temperature.[9]

However, much remains that we do not yet understand about TSQD growth and properties. For example, I have shown that GaP(111)A TSQDs grow via the Volmer-Weber mechanism, where 3D self-assembly starts immediately after deposition begins.[9] In contrast, the GaAs(111)A TSQDs of interest here appear to form via a modified ***Stranski-Krastanov (S-K)*** mechanism, where 3D TSQD growth follows 2D wetting layer formation.[13] We will advance materials science by building a complete picture of these novel nanomaterials, enabling others to use them in informed and creative ways to solve specific problems.

Feedback between sample characterization and MBE growth will accelerate our exploration of TSQD growth. We will use atomic force microscopy to measure TSQD shape, size, and areal density. We will use scanning transmission electron microscopy to image internal TSQD structure, and high-resolution high-angle annular dark field tomography to measure residual TSQD tensile strain. Quantifying the tensile strain remaining in the TSQDs after growth is critical for understanding their band structure. To ensure accurate strain measurements, we will therefore use two other techniques in parallel. Micro-Raman spectroscopy is a powerful tool for measuring strain from changes in the characteristic vibrational resonances of atomic bonds. In addition, I have previously shown how to use x-ray diffraction for extracting the total strain in QDs by stacking them in layers.[40]

TSQD optical properties. It is fundamentally important that we understand the unusual, potentially transformative optical characteristics of TSQDs, and how they vary as a function of MBE conditions. For rapid feedback to MBE growth we will optically characterize TSQD samples at Boise State University using PL. For more complex, high-resolution optical spectroscopy, I will continue my fruitful collaboration with ***Prof. Gregory Salamo (University of Arkansas)***. The first data we produced together on TSQD light emission was reported in *ACS Nano*, followed by a study of tensile-strained nanowires.[38, 39] Salamo's group is world-renowned for state-of the-art optical spectroscopy of various nanomaterials, including QDs.[41–47] The team has expertise in Raman spectroscopy, temperature-, polarization-, power- and time-resolved PL/PLE, μ-PL, pump-probe, and Fourier-transformed infrared and terahertz spectroscopy. Unraveling the combined effects of strain, quantum confinement and composition on TSQD emission will benefit other materials scientists by creating a "tool-box" for the design and synthesis of new optoelectronic nanomaterials.

Criteria for completion. To measure completion of this objective, we will report:

- The range of MBE conditions over which we can grow defect-free GaAs/InAlAs(111) TSQDs.
- The use of MBE to control TSQD structure, areal density, residual strain and optical properties.
- Close feedback between characterization and MBE synthesis for rapid material development.

Objective 2: Explore TSQD nucleation and growth at atomic levels

The innovation of using tensile-strain to drive QD self-assembly on (111) surfaces presents us with an opportunity for integrating previously incompatible materials. This objective will complement the experiments in objective 1 by building a comprehensive understanding of how TSQD growth initiates at the atomic scale. Output from this objective will provide the research community with the knowledge they need to start using tensile-strained self-assembly for novel materials integration.

TSQD island scaling experiments. To explore TSQD nucleation and growth at the atomic level, we will use an approach known as island scaling theory. Scaling theory was first developed to explain the growth of homogeneous, and later, heterogeneous 2D material systems.[48–51] More recently, its use has been expanded to 3D, to describe S-K self-assembly of traditional, compressively strained QDs.[52–54] Scaling theory is extremely powerful. Using analytical fits to scaled island size distributions allows us to identify the critical cluster size, i, defined as being one less than the number of atoms required to form a stable TSQD nucleus (***Fig. 6***).[55] Scaling theory also provides insight into the kinetic processes of QD growth, and enables us to predict island size distributions *a priori*.

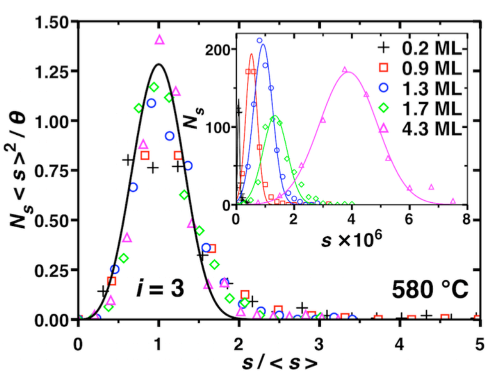

Fig. 6: Island scaling in GaP(111)A TSQDs grown at 580 °C. Scaled TSQD size distributions with different GaP deposition thicknesses. Black line is an analytic curve for critical cluster size $i = 3$ (see [55]). Inset shows unscaled TSQD size distributions.[9]

In earlier work on GaP TSQDs I showed that tensile-strained self-assembly appears to obey island scaling.[9] This is further evidence that the kinetic rules underlying compressive self-assembly also govern the nucleation and growth of TSQDs (***Fig. 6***). I intend to leverage that previous research to carry out a detailed experimental investigation of island scaling in GaAs/InAlAs(111) TSQDs. Understanding how critical cluster size varies as a function of MBE conditions will give us insight into what is happening at the atomic scale during the very earliest stages of TSQD formation. We will map island scaling dependence over the entire growth parameter space for TSQD self-assembly.

Modeling TSQD scaling and self-assembly. We will support these experiments with feedback from computational modeling of island scaling in TSQD nanomaterials. We will collaborate with ***Prof. Christian Ratsch (UCLA)***; Ratsch and I became colleagues when I ran the Integrated NanoMaterials Laboratory at UCLA. Our group worked with Ratsch on several computational papers.[56–58] Ratsch uses computational modeling techniques including ***density functional theory (DFT)***, kinetic Monte Carlo, and island dynamics simulations to explore epitaxial growth and its effect on material properties.[59–63] Ratsch created some of the earliest computational models of island scaling during epitaxial growth, and now has more than 20 years of experience in this field.[60, 64–66] He has also investigated nanostructure self-assembly on (111) surfaces, and the effect of tensile strain on epitaxial growth.[56, 57, 62, 63, 65, 67] Ratsch is hence the ideal person to model island scaling in (111)-oriented TSQDs.

Understanding how proto-QD islands nucleate during self-assembly is complex since critical cluster size is highly dependent on MBE conditions.[57] Data from the experiments above will inform the modeling, enabling calculations for GaAs growth on InAlAs(111)A, and (111)B to uncover atomic-level detail of TSQD growth initiation. Understanding how dimer dissociation and detachment rates vary as we move from compressive to tensile strain will help us predict the uniformity of TSQD size distributions.[67]

The interplay between experiment and modeling in this objective will accelerate discovery in these novel nanomaterials. Benefits of the resulting dataset will be twofold: it will help us control GaAs(111) TSQD density and size distributions for optimized photon entanglement; and it will give other materials scientists the atomic-level detail they need to begin creating their own tensile-strained nanomaterials.

Modeling TSQD band structure. Subject to securing additional funding, Ratsch will also help us study GaAs(111) TSQD band structure. Tensile strain reduces semiconductor band gaps by lifting the ***heavy-hole (HH)*** and ***light-hole (LH)*** degeneracy.[68] In GaAs, tensile strains << 1% are sufficient to push the LH band above the HH band, creating a LH exciton ground state.[69, 70] We will use the latest DFT codes calculate GaAs band structure under tensile strain.[58, 71, 72] If carried out, this optional task will certainly support aspects of objective 3, but overall project success is not contingent on its completion.

Criteria for completion. To measure completion of this objective, we will demonstrate:

- Rules for island scaling and critical cluster size as a function of MBE conditions.
- Models that predict how to grow TSQD arrays with a given size or areal density.
- How GaAs TSQD band structure depends on tensile strain (conditional outcome).

Objective 3: Demonstrate photon entanglement in TSQDs

Our results showing that GaAs(111) TSQDs have very low FSS are an excellent starting point.[13] Objective 3 is to build on that preliminary data and demonstrate entangled photon emission from TSQDs.

TSQD optimization for quantum spectroscopy. Using the outcomes of objectives 1–2, I will fine-tune TSQD synthesis to create samples with enhanced photon emission. I will focus on optimizing two key areas: **(1)** reducing FSS to negligibly low values for increasingly robust photon entanglement; and **(2)** enhancing TSQD uniformity across samples. Demonstrating self-assembled GaAs(111) TSQDs with vanishingly small FSS will fulfill their theoretical promise.[11] Our island island scaling results will help us sharpen TSQD size distribution across each wafer. Sharp distributions will ensure that the TSQDs emit photons within a narrow energy band, which will be important for demonstrating the scalability of this technology in objective 5. Due to high adatom mobility on (111) surfaces,[10] I have already demonstrated TSQD densities below 10^9 cm^{-2} (i.e. ~10 times lower than for traditional QDs).[9] Since subsequent spectroscopy experiments will rely on measuring photon emission from single TSQDs, we will leverage this insight to target very low areal densities and minimize crosstalk from neighboring dots.

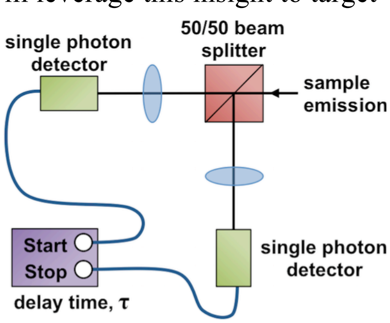

Fig. 7: Schematic of the HBT setup to measure $g^{(2)}(\tau)$. Single photon emission is revealed by photon anti-bunching since a QD can't simultaneously emit two photons.

Single photon emission and magneto-optical spectroscopy. To confirm triggered single photon emission from TSQDs we must demonstrate photon anti-bunching, characterized by a dip in the second-order autocorrelation function at zero time delay, $g^{(2)}(0)$. I will continue my productive collaboration with ***Prof. Sven Höfling (University of Würzburg)*** for this task. Höfling's group has a distinguished international reputation for ultrahigh-resolution spectroscopy of nanostructures. They performed the preliminary FSS measurements on GaAs(111) TSQDs shown above.[13] To confirm single photon emission, we optically pump individual TSQDs with a continuous wave laser. After transiting a high energy resolution monochromator, the collected photons pass into a fiber-coupled ***Hanbury-Brown and Twiss (HBT)*** setup (***Fig. 7***) with a timing resolution of ~490 ps. We use the time delay, τ, between detection events to plot $g^{(2)}(\tau)$. We can also use a pulsed pump laser to verify that we can trigger single photon emission on demand. By placing samples in a magnetic field during μ-PL, we can investigate the exciton probability density as a function of TSQD anisotropy, strain, and piezoelectric interactions.[73] This powerful analytical tool will allow us to determine the physical mechanisms governing TSQD optical emission. In addition, Zeeman-splitting measurements will reveal a great deal about selection rules in TSQDs. Selection rules dictate which electronic transitions are allowed, and are well understood for traditional QDs.[74–77] Intriguingly, it seems that these established selection rules can sometimes be broken in unstrained (111)-oriented QDs.[78] It will be extremely interesting to see if (111) TSQDs also exhibit this highly unusual behavior, or if the tensile strain somehow alters their response.

Light-hole excitons. Since excitons are central to generating polarization-entangled photons (***Fig. 1***), understanding TSQD excitonic properties is crucial. We saw in objective 2 that tensile strain lifts the ***light-hole (LH)*** band above the ***heavy-hole (HH)*** band (i.e., the opposite of what happens in traditional, compressive QDs). This leads us to predict that TSQDs have a LH exciton ground state (i.e., an electron bound to a light-hole), which is very unusual but potentially extremely useful. A single photon source based on LH excitons is needed to realize at least one proposed strategy for quantum interfaces in distributed quantum networks.[79] The second task I work on with Höfling's group will thus be to investigate TSQDs for these unconventional and very desirable LH excitons. The Schmidt group (IFW Dresden) used piezoelectric actuators to stretch unstrained GaAs QDs and transition from HH to LH excitons (***Fig. 8***). [80–82] The advantages of probing LH exciton behavior with TSQDs rather than the Dresden approach are that the 3.8% tensile strain in GaAs TSQDs is far larger than can be achieved mechanically, and it we obtain it without bulky piezoelectric actuators or complex processing. TSQDs are thus well suited to future device fabrication. We will confirm the presence of LH excitons in GaAs(111) TSQDs, and study their suitability for on demand single photon emission.

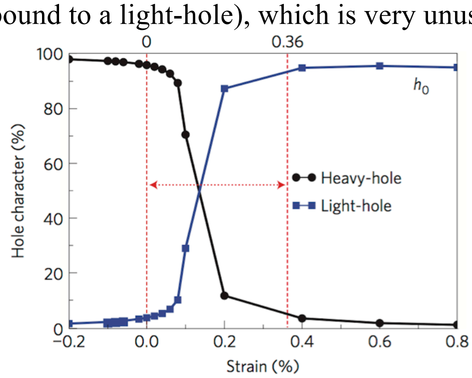

Fig. 8: Tunability of ground state hole character in a GaAs QD as a function of in-plane biaxial strain ($x > 0$ = tensile strain). Light-hole character dominates for tensile strains >0.2% (from [81]).

Polarization entanglement of photon pairs. For this key task my students and I will collaborate with ***Drs. Samuel Carter***, ***Allan Bracker*** and ***Dan Gammon (Naval Research Laboratory, NRL)***. NRL is well known for cutting-edge work on entanglement in coupled QDs.[83–86] We will confirm photon entanglement in TSQDs by modifying the HBT setup in ***Fig.*** *7*. By inserting λ/2 and λ/4 plates after the 50/50 beam splitter, and rotating them to specific angles, we can detect all possible polarization combinations of the two-photon state. [24, 87] We can build the two-photon density matrix from the $g^{(2)}(\tau)$ intensity at $\tau = 0$ for each arrangement. By comparing this matrix to theory and its fidelity to the maximally entangled Bell state, we will quantify the degree of entanglement.

Criteria for completion. To measure completion of this objective, we will report:

- Optimized growth of low FSS, high uniformity TSQD arrays with low areal density.
- Triggered single photon emission and light-hole exciton behavior in TSQDs.
- The degree and fidelity of polarization entanglement in photon pairs emitted from TSQDs.

OBJECTIVE 4: INVESTIGATE FIBER-COMPATIBLE ENTANGLED PHOTON EMISSION

For entangled photons to eventually be useful in real-world applications, it is essential that we can transmit them via optical fiber with minimal loss. Absorption loss in optical fibers is minimized in the ***short-wave infrared (SWIR)***, at photon energies of ~0.95 eV (λ ≈ 1300 nm: the "O-band") and ~0.8 eV (λ ≈ 1550 nm: the "C-band"). We have demonstrated photon emission from TSQDs with energies as low as 1.18 eV.[13] To push TSQD emission to the O-band, we must reduce photon energy by ~230 meV; for C-band we need a ~380 meV reduction. Traditional InAs/GaAs(001) QDs emit light at 1–1.3 eV, but reducing photon emission energy further out into the SWIR has been a challenge.[88–90] Compressive strain in those QDs *increases* photon energy, so moving in the opposite direction is not trivial. In contrast, tensile strain reduces TSQD band gaps, helping push photon energy *towards* the SWIR.[13, 38, 39]

I intend to create TSQDs that operate in the SWIR. I can reduce TSQD photon energy by increasing the tensile strain or by making them from a lower band gap semiconductor. To increase TSQD tensile strain I can tune InAlAs barrier composition. To lower the band gap, I can add small amounts of In or Sb to the GaAs(111) TSQDs. Using a combination of these two approaches, I aim to reduce the emission energy from 1.18 eV in our current GaAs(111) TSQDs to 0.8–0.95 eV, where suddenly these photons become useful for long-distance fiber transmission.

We will repeat the single photon and entanglement measurements on SWIR TSQDs. Quantum spectroscopy in the SWIR is complicated by the fact that many groups use single photon detectors that can only measure photons with energies ≥ 1.12 eV (the band gap of silicon). However, my collaborators at NRL have a mutual interest in fiber-compatible QDs and intend to develop SWIR quantum spectroscopy capability. I anticipate work on objective 4 ramping up in project years 3–4 (see Research Timeline), by which time the NRL team should be ready for SWIR measurements. Fiber-based transmission of entangled photons will be a significant step forward for these novel TSQD nanomaterials.

Criteria for completion. To measure completion of this objective, we will report:

- Development of low band gap TSQDs that emit SWIR fiber-compatible photons.
- Our ability to achieve single photon emission and polarization entanglement in SWIR TSQDs.

OBJECTIVE 5: FABRICATE PROOF-OF-CONCEPT DEVICES

Tensile-strained self-assembly advances the field by offering a new way to integrate materials for advanced optoelectronic applications. Outcomes from objectives 1–4 will enable me to design and build prototype TSQD light-emitting diodes (LEDs) to demonstrate on demand, entangled photon emission. These electrically driven, entangled photon sources will capitalize on the superior crystal quality, and planar device architectures of TSQD nanomaterials.

My former group at University of Cambridge/Toshiba first demonstrated an entangled LED based on QDs in 2010, proving that this is a viable prospect.[91–93] However, since their device was based on traditional, compressive QDs with large FSS, only ~1% of the QDs showed robust entanglement.[91] Although their results are very impressive, it is clear that for future commercialization, the proportion of QDs with low FSS must be closer to 100%. ***Fig. 4*** shows that even in our rudimentary initial samples, 62% of randomly selected TSQDs had FSS ≤ 10 μeV (~40% had FSS ≤ 5 μeV), values low enough for entanglement. What is more, TSQDs deliver the required performance *as-grown*. The single-step growth of TSQDs with naturally low FSS removes the need to painstakingly search for suitable QDs, or to tune their FSS with electric fields and post-growth treatments.[7, 23, 25, 26] These preliminary results thus suggest TSQDs are an inherently more scalable platform for entangled LED fabrication. The ability to make devices with similar performance from across a 3” sample is essential for future manufacturing.

Design and fabrication of entangled LEDs. Using previously published LED structures as a starting point,[91–93] we will design a TSQD entangled LED to demonstrate proof-of-concept. To increase photon collection efficiency we will place the TSQDs within an optical microcavity.[7, 91, 94–97]

We will fabricate these prototype devices in the Idaho Microfabrication Laboratory at Boise State and in the cleanroom at NRL. The (111)A and (111)B surfaces of our samples have different atomic reconstructions to the traditional (001) surface. This fact will likely require us to modify our standard processes, for example, choice of etch chemistry or electrical contact metals. To confirm viability we will first develop LEDs from the GaAs(111) TSQDs developed in objectives 1–3. We will then transfer this process to the SWIR TSQDs from objective 4, adjusting our design as needed for lower energy photons.

Entangled LED device testing and scalability. To characterize proof-of-concept device operation we will work with our collaborators at Würzburg and NRL. These measurements will mirror the optically pumped spectroscopy described in objective 3, but here the aim will be to demonstrate *electrically driven*, on demand emission of single photons and entangled photon pairs, ideally at fiber-compatible energies. The final stage of the research project will be to show the scalability of this technology by quantifying performance variation between entangled LEDs created at different points across a large-area sample.

Criteria for completion. To measure completion of this objective, we will report:

- Design and fabrication of proof-of-concept entangled LEDs based on GaAs and SWIR TSQDs.
- Prototype device performance in terms of scalable, on demand emission of entangled photons.

EDUCATION AND OUTREACH PLAN

My tenure-track appointment is held jointly between ***Materials Science & Engineering (MSE)***, and Physics. As in STEM departments all over the country, gender and ethnic diversity at Boise State is low, both among students and faculty. Therefore, my education and outreach goals are to help redress this diversity imbalance, reduce classroom attrition, increase STEM graduation rates, and ultimately enhance STEM workforce development. To do so, I will extend quantum cryptography content, integrally related to the research plan, as part of a multi-pronged ***service-learning (SL)*** program. Doing so will expand research impact, while simultaneously building the STEM pipeline via outreach to students, their teachers and communities. The educational activities I establish in this project will underpin a career-long emphasis on increasing the participation of women and other underrepresented groups in STEM careers.

EDUCATION GOAL AND OBJECTIVES

To meet the goal of increasing diversity in STEM careers, I will complete the program objectives below:

1. ***Develop STEM educational content***—Build a service-learning component into undergraduate class. Students create cryptography-based activities to teach key STEM concepts to 4–6 grade students.
2. ***Elementary school STEM education***—Undergraduates work with Discovery Center museum to build activities into outreach events for 4–6 grade students in low socioeconomic status communities.
3. ***Teacher professional development—***Collaborate with i-STEM program to provide Idaho teachers with training, knowledge and resources to implement these STEM activities in their own schools.
4. ***Community/family STEM outreach***—Refine STEM activities to contribute cryptography/cyber-security content to the monthly "Adult Night" at the Discovery Center.

BACKGROUND

Why is enhancing diversity so important? NSF, Boise State University and I share the goal of raising the number of historically underrepresented people who pursue STEM careers. Increased diversity positively impacts the developmental and educational experiences, creativity and problem solving ability of all students.[98–100] A pool of new talent consisting of graduates from underrepresented groups would directly benefit me in my search for exceptional research students. More generally, it would help STEM-based industry and academic departments nationwide achieve their aim of increased workforce diversity.

What are the problems? Many undergraduates who embark on STEM degrees later move to other majors, and persistence and retention rates are especially low among underrepresented students. ***Fig. 9(a)*** shows that in 2013, women earned only 36.1% of Bachelor degrees in STEM (compared to 57.1% across all subjects), with engineering and physics showing the lowest proportions of female graduates (19.3% and 19.6%, respectively).[101] Compounding this issue is the fact that women make up only a tiny fraction of full professors: just 8% in physics, according to 2010 figures from the American Institute of Physics. Fewer women in the highest academic positions means fewer role models for female students considering STEM careers. Encouraging new research suggests the tide may finally be turning for women in STEM academic careers,[102] but a great deal of work is still needed to boost STEM participation across all underrepresented groups.

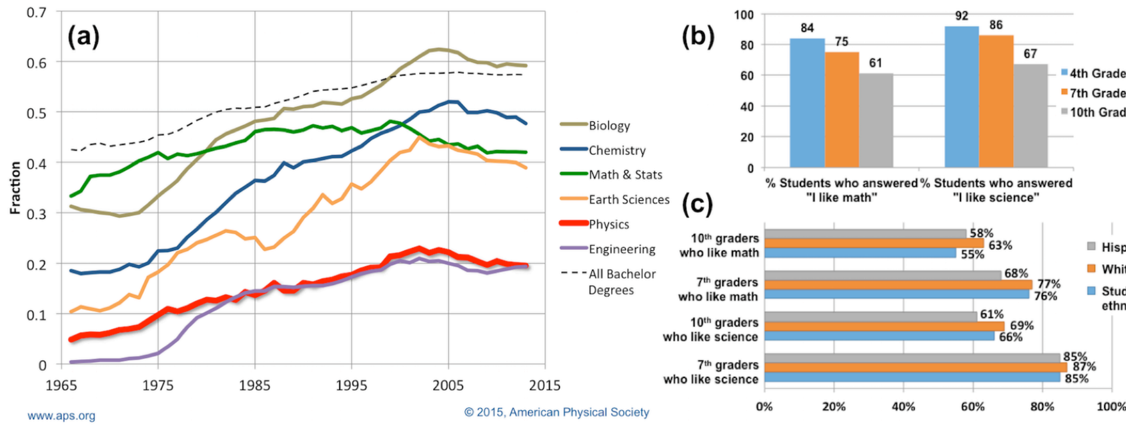

Fig. 9: (a) Fraction of STEM Bachelor degrees earned by women, by major.[101] (b) Student interest in STEM declines with age. (c) This decline is consistently lower among non-white students.[104]

What causes these problems? Recent Idaho-based research shows we can trace these problems back to early in a student's education.[103, 104] Student interest in STEM declines with progress through school (***Fig. 9(b)***), and this drop is especially steep for underrepresented students (***Fig. 9(c)***). Authors identified several factors that stifle a student's early interest in STEM.[103, 104] These obstacles to retaining students for STEM careers include: **(1)** a lack of experiential opportunities; **(2)** a lack of student and family awareness of STEM career opportunities; **(3)** a lack of teacher development in integrated STEM education; **(4)** cultural barriers; and **(5)** poor support from family and community members for STEM students. For example, the study found that Idaho family members often feel unable to help students with math and science, and discovered that the Hispanic community distrusts scientists, finds the educational system difficult to navigate, and has little interest in STEM.[103] For Hispanic students interested in STEM, these influential social factors could eventually persuade them to pursue other disciplines.

Preliminary Education Results and Relevant Expertise

In structuring my response to these serious issues for STEM education, I describe past experiences with teacher and student educational outreach that have helped inspire the program I propose here.

Teacher professional development. In my previous position at UCLA, I volunteered for several years with the hugely successful High School Nanoscience Program. Teachers from across Los Angeles, many working in low socioeconomic status communities, attend monthly workshops at UCLA. Teachers receive training and resources to run classroom nanoscience experiments, and are shown how the experiments align with California's science education standards. They then transfer the experiments to their high school students, helping students learn that STEM is an exciting and relevant part of daily life. Teachers participating from more than 200 schools have reached thousands of students, magnifying program impact. Teacher response suggests that they feel motivated, supported and encouraged.

NSF Research Experiences for Undergraduates (REU). This year I explored engaging ways to discuss quantum entanglement with students outside my core departments. Profs. Liljana Babinkostova and Marion Scheepers coordinate an annual Mathematics REU program at Boise State. Since student research projects reflect faculty interest in cryptography, the faculty invited me to give a talk on quantum cryptography at this year's event. Audience feedback about my ability to communicate these abstract concepts represents invaluable preliminary data for my education and outreach plan.

Education Plan Methodology

Here is context about my proposed service-learning strategy. I will use four program objectives to address the causes of STEM student attrition listed above, through cyclical development, implementation, assessment and improvement. A portion of the budget is allocated to cover educational outreach costs.

Service-learning as a solution. I propose an integrated educational outreach program designed to address the obstacles to STEM participation listed above. I place particular emphasis on reaching women and underserved communities in Idaho in a culturally relevant manner. As children navigate towards potential STEM careers, I believe it is crucial to consider the route from pre-kindergarten to twelfth grade holistically. We must build an environment where attitudes in schools, families and society: ***a)*** actively encourage a student's early interest in STEM, regardless of gender or background; and ***b)*** provide consistent nurturing and support of that interest at every educational stage. To this end, my educational outreach program focuses on students of different ages, their teachers, and the wider community. My strategy (***Fig. 10***) for reaching these audiences centers on ***service-learning (SL)***, which integrates academic subject matter with service to the community. Key elements include reciprocity, reflection, coaching, and enabling a community voice. ***Boise State has made a particular commitment to this strategy by creating a dedicated Service-Learning Unit.*** This Unit facilitates more than 120 service-learning courses each year in partnership with more than 30 departments, 80 faculty, 100 community partners, and about 2,500 students. Most faculty use SL strictly to connect classroom and community. My proposed work further extends the SL opportunity by integrating research plan content, and targeting multiple audiences.

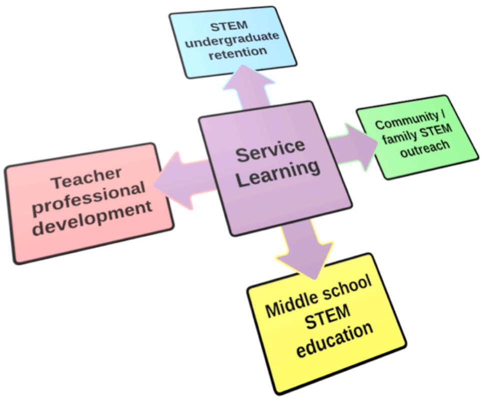

Fig. 10: Service-learning supports all aspects of the proposed STEM education/outreach.

Studies have long demonstrated that SL increases student persistence in college.[105–110] The American Association of Colleges and Universities list SL as a "high impact practice" that has a pronounced and positive effect on student learning measures such as grade point averages and retention, particularly in STEM fields and among underrepresented groups.[111–116] These groups often cite a desire to solve social problems as a prime reason for choosing a STEM career.[112] A recent New York Times article,[117] entitled *How to Attract Female Engineers* states, "if the content of the work itself is made more societally meaningful, women will enroll in droves." SL achieves precisely this goal.

Integrating quantum cryptography. Public interest in cryptography is clear from the success of "The Code Book" by Simon Singh,[118] and the movie "The Imitation Game," as well as frequent news reports about Internet security lapses. Our increasing reliance on the Internet for daily activities (banking, purchasing, viewing medical records, etc.) shows people the importance of data security. Integrating cutting-edge materials science research will bring the outreach to life.

OBJECTIVE 1: DEVELOP STEM EDUCATIONAL CONTENT

This objective addresses undergraduate persistence and retention, particularly among underrepresented groups. I will build a SL component into my class PHYS 309: *Introduction to Quantum Physics*. This class is predominantly taken by MSE and physics majors, and numbers about 45 students. The new SL component will be an optional, one-credit course co-requisite, requiring each student to commit 45 hours.

The SL students and I will partner with Kristine Barney, Executive Director of the ***Discovery Center of Idaho (DCI)***. DCI is a non-profit science museum in Boise featuring interactive, child-friendly exhibits that explain complex ideas. DCI educators are highly experienced at turning difficult scientific concepts into engaging learning experiences for all ages. SL students will work with DCI educators to create activities that use quantum cryptography to teach key STEM concepts to 4–6 grade students. ***Fig. 9(b)*** summarizes the motivation for targeting this age group; reinforcing student interest in STEM at this age can be transformative, encouraging students to develop STEM identities that evolve into culturally relevant STEM careers. These children are still young enough to accept at face value the fact that science sometimes predicts the unexpected. The weirdness of quantum entanglement gives us a great opportunity to "blow their minds" with a phenomenon that even Einstein called "spooky." We will show them how even things as strange as entanglement can be used by materials scientists to help us in our daily lives.

Our small group, hands-on activities will promote skills recognized as central to success in STEM, such as critical thinking, collaboration, communication, and leadership. It is also critical that the activities are squarely aligned with Idaho's Core Standards for STEM education.[119] We will pilot the activities with one or two local elementary schools and refine the activities before expansion in objective 2.

Objective 2: Elementary school STEM education

This objective addresses the lack of experiential STEM opportunities and student awareness of STEM career opportunities. Here SL students will work with DCI educators to package their cryptography STEM activities into outreach events for 4–6 grade students at three local community centers. Whitney, Grace Jordan, and Morley Nelson community centers are all based in predominantly Hispanic, low socioeconomic status neighborhoods. By selecting these particular centers we can target our outreach to students from backgrounds historically underrepresented in STEM disciplines.

The main aim is to help prepare scientifically literate elementary school students. However, by using the accessible and fun theme of making and breaking codes, I also want to reengage students for whom STEM may have lost its appeal. As children work with college role models on these hands-on activities (particularly girls paired with female undergraduates) we hope they begin to see themselves as scientists, and to aspire to STEM success. The children will learn how materials science research can directly impact their world, and that a career in STEM can be exciting and rewarding. The SL undergraduates will learn a wide range of highly transferrable skills: to communicate complex ideas to an untrained audience; to see themselves as STEM experts during their interactions with the public; and to work within guidelines on an open-ended task. Participant evaluations will help us improve the activities year on year.

Objective 3: Teacher professional development

This objective addresses teacher development and cultural barriers. In 2010, Idaho launched ***Integrated-STEM (i-STEM)***, to provide STEM teachers with professional development and educational resources. I will collaborate with Anne Seifert (i-STEM Executive Director) to work with 4–6 grade teachers from Idaho and surrounding states. Each year, six regional i-STEM education centers host approximately 700 teachers at summer institutes to promote project-based learning integrated across disciplines. As teachers take these concepts back to their classes, thousands of regional elementary school students benefit. To facilitate extended learning transfer, the i-STEM centers provide physical, financial and technological resources, and ongoing teacher support including human resources, instructional materials, and stipends.

In project years 2–5, I will lead a strand at i-STEM to leverage cryptography-based activities developed in of objectives 1–2. We will provide teachers with a custom-designed STEM lesson plan, and the training and resources needed to run the lesson in their classrooms. We will also show the teachers how educational outcomes align with the Idaho Core Standards for science. ***Of key importance, training will include a cultural competency component to help teachers find ways to reach a diverse student body***. I will continue to support teachers after the summer institute who choose to implement the STEM activities. Teacher evaluations will enable continuous improvement of activities, training, and resources.

Objective 4: Community / family STEM outreach

This objective addresses cultural barriers and the role of family and community members. Adult members of a student's community are a vital part of their learning environment. Consciously or unconsciously, they can influence student interests and choices, and play a key role in their educational success (***Fig. 10***).[104, 120] Those who understand the value of STEM careers are far more likely to support and encourage students interested in pursuing these goals.

DCI hosts a monthly "Adult Night" where 200–500 members of the public interact with scientists. I will modify the activities from objectives 1–3 for adults to contribute "cyber-security" content to this event. Attendees will learn about innovative materials research at their local university, how it relates to them, and the rewarding career opportunities available to STEM graduates. Reinforcing these concepts over time will positively inform the public perception of who a scientist or engineer is and what she or he does, making it easier for adults to help community children to identify with and aspire to STEM careers.

Criteria for completion. To measure the success of the four educational outreach objectives I will leverage surveys, interviews and student enrollment data for formative and summative assessment to:

- Look at the extent to which taking part in cryptography-based activities affects interest of elementary school students in STEM subjects and careers.
- Examine relationships between teacher participation in i-STEM development activities, and their willingness to teach STEM in an integrated way and better reach their underrepresented students.
- Identify changes in understanding of cyber-security concepts and attitudes towards STEM fields among community participants at DCI public outreach activities.
- Investigate impact of SL participation on STEM field undergraduate persistence and retention.

Assessment

On-going assessment will be critical to the progress and overall success of the integrated research, and education and outreach plans. For the latter, we will examine both short-term activity outcomes and student response to SL experiences, as well as longer-term STEM undergraduate persistence, retention, and graduation rates. Annual evaluation of all project activities against the completion criteria and timelines (below) will demonstrate progress, reveal obstacles to success, and ensure we adhere to the project schedule. We will summarize outcomes in the annual NSF project report, and make adjustments for ongoing improvement. Products such as peer-reviewed publications, conference presentations and patent applications will provide additional progress measures and extend impact. I will collaborate with the STEM Institute and Service-Learning Unit at Boise State to acquire the evaluation and assessment instruments I will need, e.g., for measuring student interest in out-of-school STEM activities.[121] I have budgeted support for an undergraduate researcher to help collect and analyze assessment data.

Project Management

Here is information about key personnel, my plans for project coordination and risk mitigation, timelines, and actions to ensure future sustainability of the research and educational outreach.

Key personnel

The proposed budget funds the PI, one Ph.D. student researcher, and one undergraduate researcher.

Paul Simmonds (PI, Boise State University) – I will lead and direct the proposed work. My research group will carry out TSQD nanomaterial growth and structural characterization. I will coordinate collaborative subtasks by drawing on project management experience in both academia and industry. In my prior position, I ran a successful MBE recharge center at UCLA managing budgets, developing workforce, building collaborations, training students, driving research, and writing grant proposals.

Unfunded collaborators

Based on ***unfunded but mutually beneficial partnerships***, I have assembled an interdisciplinary team of scientists, and educational specialists. Guidance and mentoring from highly experienced researchers will be a huge benefit to my career development. I include a letter of collaboration from each of the following:

- ***Greg Salamo*** (University of Arkansas) – His group will partner on optical and structural characterization of TSQD nanomaterials.
- ***Christian Ratsch*** (UCLA) – His group will partner on modeling island scaling in tensile-strained self-assembly, and TSQD band structure.
- ***Sven Höfling*** (University of Würzburg) – His group will partner on single photon measurements, magneto-optic effects, and exploring light-hole excitons in TSQDs.
- ***Sam Carter***, ***Allan Bracker, Dan Gammon,*** (U.S. Naval Research Laboratory) – NRL will partner on correlation and entanglement measurements, mid-IR TSQD measurements and device development.
- ***Kristine Barney*** (Discovery Center of Idaho) – DCI will partner with Boise State SL undergraduates to develop cryptography-based activities for underrepresented elementary school students.

- ***Anne Seifert*** (i-STEM / Idaho National Laboratory) – i-STEM will partner to deliver educational content based on cryptography to 4–6 grade teachers across Idaho.
- ***Donna Llewellyn, Kara Brascia*** (Boise State) – Institute for STEM & Diversity Initiatives and the Service-Learning Program will partner to develop education and outreach assessment tools.

COMMUNICATION AND RISK MITIGATION

My ongoing collaborations with Salamo and Höfling are productive due to efficient communication between our groups. To review, evaluate, and direct the project, I will use the same model of regular emails, phone and video calls, and in-person conference meetings as I collaborate with my other partners. Barney and Seifert are both based in Idaho, which simplifies service-learning and outreach coordination.

Budget risks are low since it is based on established costs. Research reliance on proven equipment and infrastructure limits timeline risks. The exception is research objective 4, which relies on SWIR spectroscopy capability that NRL does not yet have. The timeline (below) for SWIR measurements is years 3–5, so we will monitor the situation with NRL in year 2. If a delay is likely, I will seek alternative collaborators with this capability (e.g., Air Force Research Laboratory). The other potential for delay is unforeseen downtime on a key piece of equipment. However, this risk is mitigated by several factors: **(1)** My collaborators and I are all experts in our respective areas, allowing us to rapidly troubleshoot issues; **(2)** We operate a strict preventative maintenance program to service or replace components known to fail periodically; **(3)** For certain key measurements (FSS, single photon, correlation, etc.) there is enough overlap between my partners that we could recover from a "worst-case scenario" project delay.

PROJECT TIMELINES

Here are five-year timelines for my research and education and outreach plans including these milestones: (**A**) Triggered TSQD single photon emission; (**B**) TSQD photon entanglement; (**C**) On-demand entangled LED operation; (**D**) First i-STEM teacher development activity; (**E**) First STEM outreach event for under-represented elementary school students.

Table 1: Research plan tasks, timetable, and milestones

	YEAR 1				YEAR 2				YEAR 3				YEAR 4				YEAR 5			
PROJECT TASKS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
TSQD growth-structure-property relations study																				
TSQD island scaling experiments / modeling																				
Single photon studies; magneto-optics							**A**													
Optimize TSQDs; show photon entanglement											**B**									
Light-hole exciton characterization																				
Growth, spectroscopy of SWIR TSQDs																				
Model TSQD band structure (optional)																				
Create / test prototype entangled LEDs																				**C**

Table 2: Education and outreach plan tasks, timetable, and milestones

	YEAR 1				YEAR 2				YEAR 3				YEAR 4				YEAR 5			
PROJECT TASKS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Design and implement SL class component																				

	YEAR 1				YEAR 2				YEAR 3				YEAR 4				YEAR 5			
SL students and DCI develop STEM content																				
4–6 grade teacher development at i-STEM							D													
Deliver STEM content to 4–6 grade students									E											
Community STEM outreach at DCI																				

FUTURE SUSTAINABILITY

I envisage this five-year project as a launch pad for my professional career. The research and STEM outreach squarely align with my long-term professional goals, and will be foundational for achieving them. Working with the STEM community will be especially formative as I interact with the latest pedagogical methods and publish my findings in education journals. I look forward to new learning opportunities as I grow my collaborations and networks. To sustain this project work beyond the award period, I will aggressively pursue additional funding sources throughout its course. I will use the data we generate to seed subsequent proposals, with potential for patents, licensing and commercialization. Finally, I believe that funding opportunities stemming from my NRL partnership are likely.

RESULTS FROM PRIOR NSF SUPPORT

The NSF has provided no prior project support to the PI.

BROADER IMPACTS OF THE PROPOSED WORK

This potentially transformative research will advance materials science by demonstrating the power of tensile-strained self-assembly for the synthesis and integration of novel nanomaterials. My education and outreach plans directly address regional needs to recruit, train, and retain a diverse, STEM-enabled workforce. To achieve this, I propose extending quantum cryptography content that is integrally related to the research plan into an undergraduate service-learning program. The program targets underrepresented elementary school students, their teachers, and communities. Workforce development is of particular importance given that Boise State University is the state's largest higher education institution. Based in Idaho's capital city, the third-largest metropolitan area in the U.S. Pacific Northwest,[122] Boise State University is a key economic engine in our EPSCoR state. Boise State is dedicated to supporting students from Idaho's two largest minorities: Hispanics (11.8%), and Native Americans (1.7%).[123] Institutional support and local i-STEM and DCI collaborations to address the challenges of increasing diversity will lead to regional and statewide benefits. My research and education activities are supported by and integrated with the goals of my department and Boise State. The mentorship of my department chair, Prof. Charles Hanna, is central to my professional development.

In addition to the formal education and outreach plan, I intend to model my commitment to diversity in my hiring choices and the way I manage my research group. My current Ph.D. student is a disabled military veteran. This award will enable to me to recruit a second Ph.D. student: an exceptional female student currently volunteering in my lab. During the project, Ph.D. and undergraduate students will acquire a range of experimental and computational skills. They will disseminate their findings in peer-reviewed journals and at conferences. Highly interdisciplinary research creates residency opportunities for the Ph.D. student to visit our collaborators and broaden their knowledge and professional network. If successful in this award, I will seek support from the NSF Office of International Science & Engineering for an extended student visit to Germany, a further boon to research and education infrastructure.

This is undoubtedly an ambitious project. However, based on exciting preliminary data, fruitful ongoing collaborations with prolific research groups, and access to world-class facilities, it is reasonable to expect that I will accomplish the proposed goals. Project success would signify an urgently needed breakthrough in materials science for quantum information applications, impacting society both nationally and globally.

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