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Hybrid Silicon/Silica Photonics Platform for Low-Power Digital Optoelectronic Switching and Logic Devices

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We demonstrated a new type of SiN resonator, that sits on the substrate, and thus is mechanically more robust.Additionally we performed a theoretical analysis of a cavity coupled to patterned 2D material to show strong antibunching is possible even in the presence of loss. This is crucial for quantum technologies. These result into two journal publications (ACS Photonics, Phys Rev. B).

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Publications to date from the AFOSR-YIP award:

1. T. Fryett, C. M. Dodson, and A. Majumdar, Optics Express 23, 16246-16255 (2015).
2. A. Majumdar, C. M. Dodson, T. K. Fryett, A. Zhan, S. Buckley, and D. Gerace, ACS Photonics 2, 1160-1166 (2015).
3. Quantum many-body simulation using monolayer exciton-polaritons in coupled-cavities, HaiXiao Wang, Alan Zhan, YaDong Xu, HuanYang Chen, Wen-Long You, Arka Majumdar and Jian-Hua Jiang, in press, Journal of Physics: Condensed Matter, (2017).
4. R. Trivedi, U. K. Khankhoje, and A. Majumdar, Phys. Rev. Applied 5, 054001 (2016).
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6. Taylor K. Fryett, Kyle L. Seyler, Jiajiu Zheng, Chang-Hua Liu, Xiaodong Xu, Arka Majumdar, 2D materials, Volume 4, Number 1, 2016.
7. Chang-Hua Liu, Genevieve Clark, Taylor Fryett, Sanfeng Wu, Jiajiu Zheng, Fariba Hatami, Xiaodong Xu, and Arka Majumdar, Nano Lett., 17 (1), pp 200–205, 2017.
8. Cavity nonlinear optics with layered materials, Taylor Fryett, Alan Zhan, Arka Majumdar, in press, Nanophotonics (De Gruyter Journal), (2017).
9. Strong photon antibunching in weakly nonlinear two-dimensional exciton-polaritons, Albert Ryou, David Rosser, Abhi Saxena, Taylor Fryett, Arka Majumdar, Phys. Rev. B, (2018).
10. Encapsulated silicon nitride nanobeam cavity for hybrid nanophotonics, Taylor K. Fryett, Yueyang Chen, James Whitehead, Zane Matthew Peycke, Xiaodong Xu, Arka Majumdar, ACS Photonics, 5 (6), pp 2176–2181 2018.

Summary on statement of objective with their status

(Green: Finished and Published; Blue: Ongoing; Red: Finished with unsuccessful attempts)

Year1:

T1: Develop integrated 2D material-silica based $\chi^{(2)}$ nonlinear optical platform

- Design ring and photonic crystal cavities in silica with resonances at multiple wavelengths. We have changed the material of choice to silicon nitride, which preserves all the properties. (2 papers are being written now on this)
- Fabricate and characterize multiply resonant photonic crystal and ring cavities
- Perform experiments to show cavity enhanced second harmonic generation from WSe_2-silicon nitride cavity. One paper on similar experiment on Silicon is published in the journal 2D materials. Another paper on related devices was published in the journal nano letters
- Analyze the parameter space of the cavities to reduce the photon number required for bistability (1 paper published in Optics Express)

T2: Explore silicon compatible nonlinear 2D materials

- Exfoliate new 2D materials ($MoTe_2$, and Black Phosphorous) with lower bandgap. We are also exploring black phosphorous on this.
- Characterize these materials in photoluminescence
- Fabricate nano-cavities in silicon-on-insulator and show coupling with $MoTe_2$ and Black Phosphorous

T3: Explore self-electro-optic (SEO) effect in silicon photonics

- Design non-resonant devices based on self-electro-optic effect

Year 2

T3: Explore self-electro-optic (SEO) effect in silicon photonics

- Optimize the optoelectronic control circuit for the SEO device
- Build prototypes of single SEO and symmetric SEO device with germanium as the photo-detector. We have changed the scope to graphene as the detector
- Build a network of SEO cavities

T4: Build Graphene-silicon ring cavity based modulator, photo-detector and SEO devices

- Demonstrate efficient electro-optic modulation with graphene-clad ring cavity
- Demonstrate photodetection with graphene-clad silicon ring cavities
- Analyze the feasibility of SEO devices based on graphene-silicon platform

Year 3

T1: Develop integrated 2D material-silica based $\chi^{(2)}$ nonlinear optical platform

- Design optically bistable device based on WSe_2-silica cavity (1 paper published in ACS photonics)
- Demonstrate low photon number (~100) optically bistable WSe_2-silica cavity system

T5: Investigate the effect of quantum noise in few photon bistable devices

- Theoretically analyze the effect of quantum noise in low photon number bistability (1 paper published in Phys. Rev. Applied)
- Observe the effect of quantum noise induced instability in the bistable device

T6: Explore different architecture for an optical computing system made of bistable devices

- Design an optical computing architecture to exploit the time-sequential gain of SEO devices
- Explore the possibility of using the bistable devices for other computing methods, including neuromorphic computing and directed logic

Here we detail the progress of the projects performed under AFOSR-YIP in the third year.

Cavity enhanced second harmonic generation in SOI platform:

Using photonic crystal cavity fabricated in silicon, we have enhanced the efficiency of the second harmonic generation in monolayer tungsten diselenide. The enhancement factor is estimated to be 200. Figure 1 shows the results from this project. We fabricated photonic crystal cavities in SOI platform, with quality factor exceeding 10,000. We then transferred tungsten diselenide monolayers on top of the cavity, which degraded the quality factor. The reason for such degradation is not quite clear, and was attributed to the transfer process. Since then, we have improved the transfer process and the quality factors of the cavities are well preserved. We pump our system with a pulsed laser near 1550nm, and observe second harmonic generation near 775nm. We also observed a cavity peak in the second harmonic signal. The cavity peak shows up exactly at the half of the cavity resonance wavelength, indicating that it is indeed the second harmonic enhanced by the cavity. We can fit the observed spectrum with a Gaussian background SHG and Lorentzian cavity peak to extract the cavity enhanced signal (Figure 1c) and observed a quadratic dependence with the input power, further indicating a second-order nonlinear process. We also measured the polarization dependence of the cavity enhanced second harmonic signal, and proved that the polarization direction is same as the cavity polarization. These results are reported in the journal 2D materials [1].

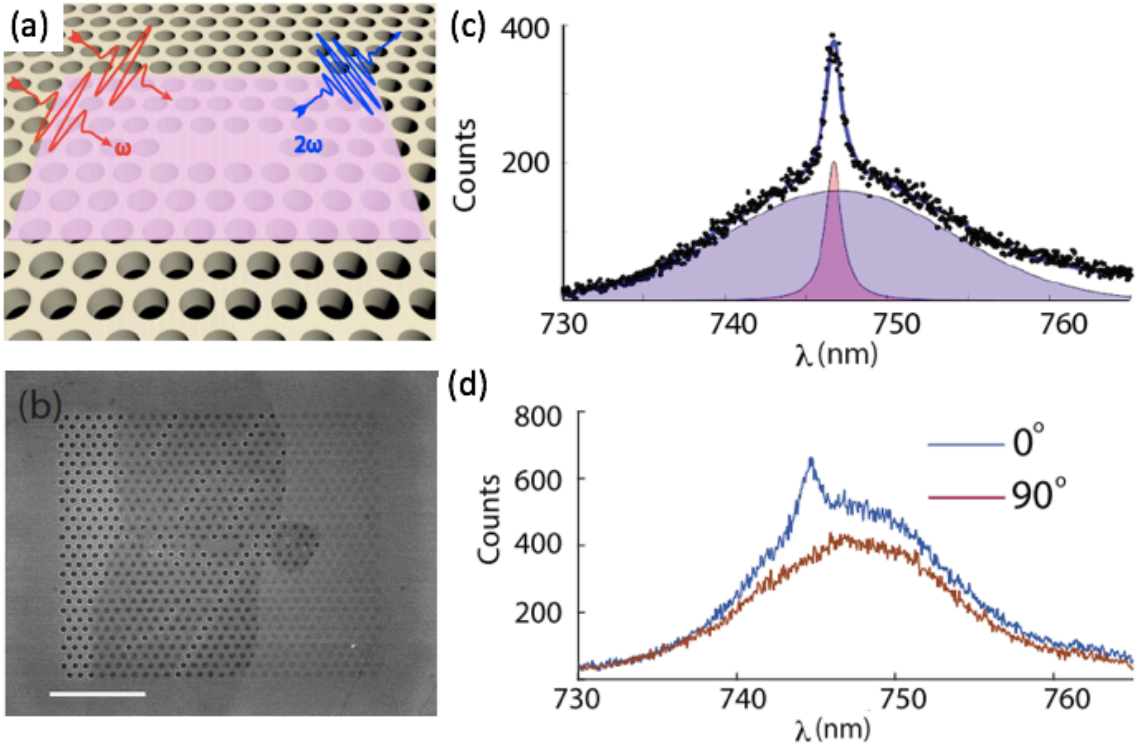

Figure 1: Cavity enhanced second harmonic generation: *(a) Schematic of second harmonic signal (SHG) process;(b) SEM of the SOI photonic crystal cavity with monolayer tungsten diselenide on top; (c) SHG spectrum shows a Gaussian background from the 2D material and a Lorentzian peak from the cavity; (d) Polarization resolved SHG spectrum shows linearly polarized cavity signal, as expected from a cavity.*

Direct modulation of cavity enhanced electro-luminescence:

Using 2D material heterostructures, we build light emitting devices, and integrated them with a photonic crystal cavity to enhance the electro-luminescence (Figure 2). The heterostructure is formed using a stack of graphene-h-BN-WSe_2-h-BN. We observed an enhancement of factor of 4, which can be further enhanced by using a higher quality factor cavity. This work was performed with gallium phosphide photonic crystal cavity, and we are currently moving towards silicon nitride platform. Additionally, in this work we transferred a cavity on the 2D material heterostructure, but going forward, we will transfer the 2D material stack on the optical resonator. We note that, these experiments are performed at room temperature. Then we demonstrate direct modulation of the light emission by applying an electric signal, with a speed of 1MHz (Figure 3). These results are reported in the journal Nano Letters [2].

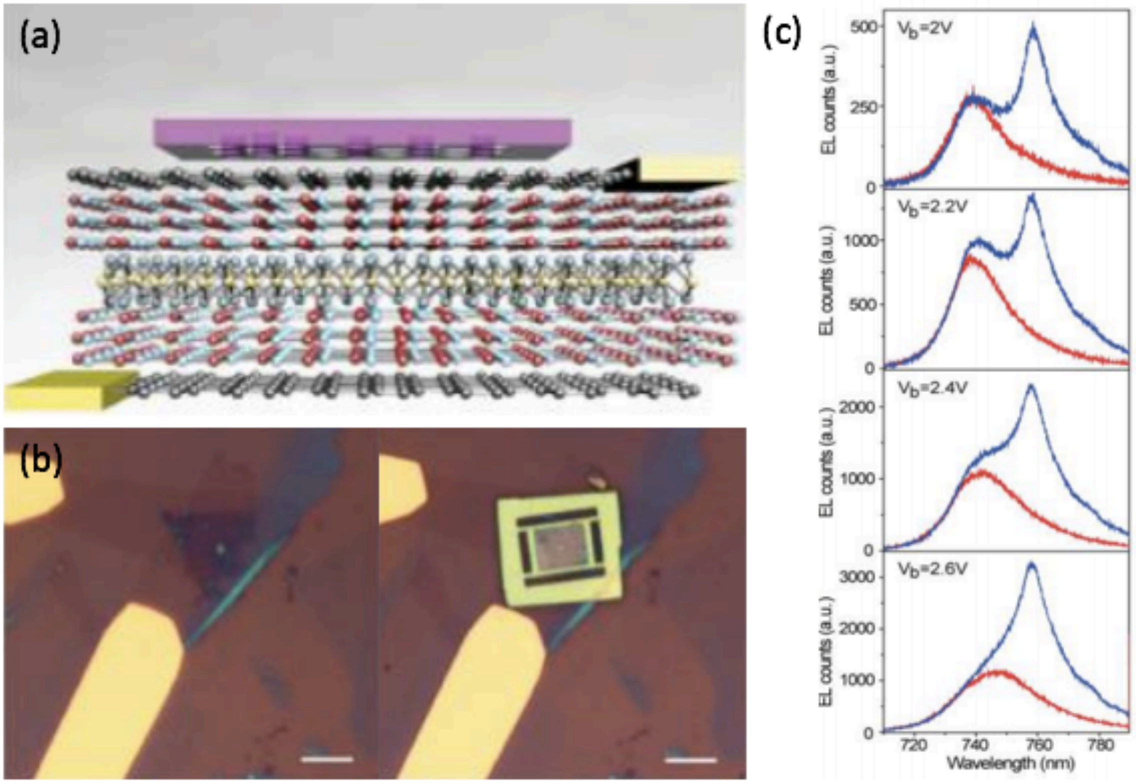

Figure 2: Light emitting diode using 2D material heterostructure, integrated with optical resonator: *(a) schematic of the device; (b) optical image of the 2D material heterostructures and of a cavity on top of the 2D material heterostructure; (c) Measured electroluminescence at two different polarization clearly shows the cavity peak, only when the light at the cavity polarization is collected.*

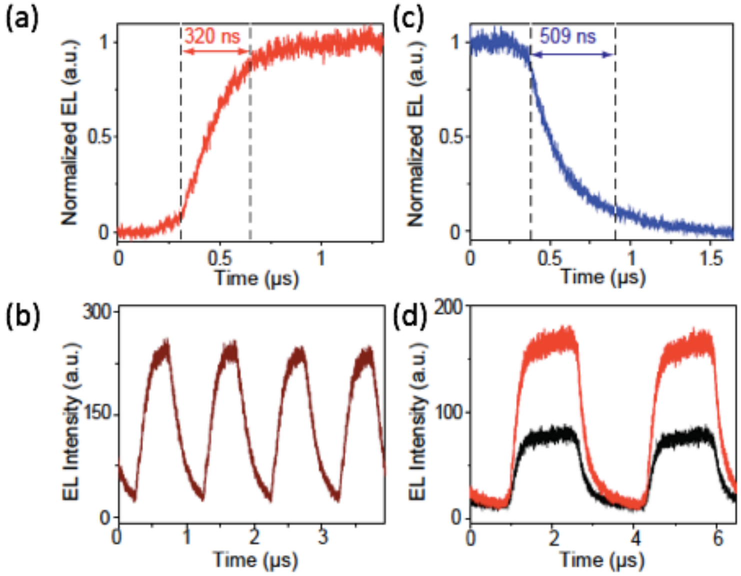

Figure 3: Direct modulation of the cavity enhanced LED: *By applying an electronic signal the light emission can be modulated. From the experiment, we can find the rise and fall time to estimate the modulation speed to be 1 MHz.*

2D material integrated silicon nitride platform:

The previous works focused on gallium phosphide due to its large band-gap (hence transparency at the exciton frequency of tungsten deselenide) and high refractive index. However, to enable CMOS compatibility, we need to use silicon or silicon nitride. Due to the large bandgap of SiN, we chose silicon nitride. We fabricated SiN disk resonators with quality factor exceeding 50,000 and probed them both using laser transmission and in photoluminescence (PL). Additionally, we fabricated SiN nanobeam cavities. Via careful design, we ensure a high Q resonance when the SiN membrane sits on the silica substrate, which makes it mechanically robust. We also characterized the cavity both in transmission and in PL. Figure 4 shows some representative SEMs, and measured transmission and PL spectrum. One paper is currently being written on this work.

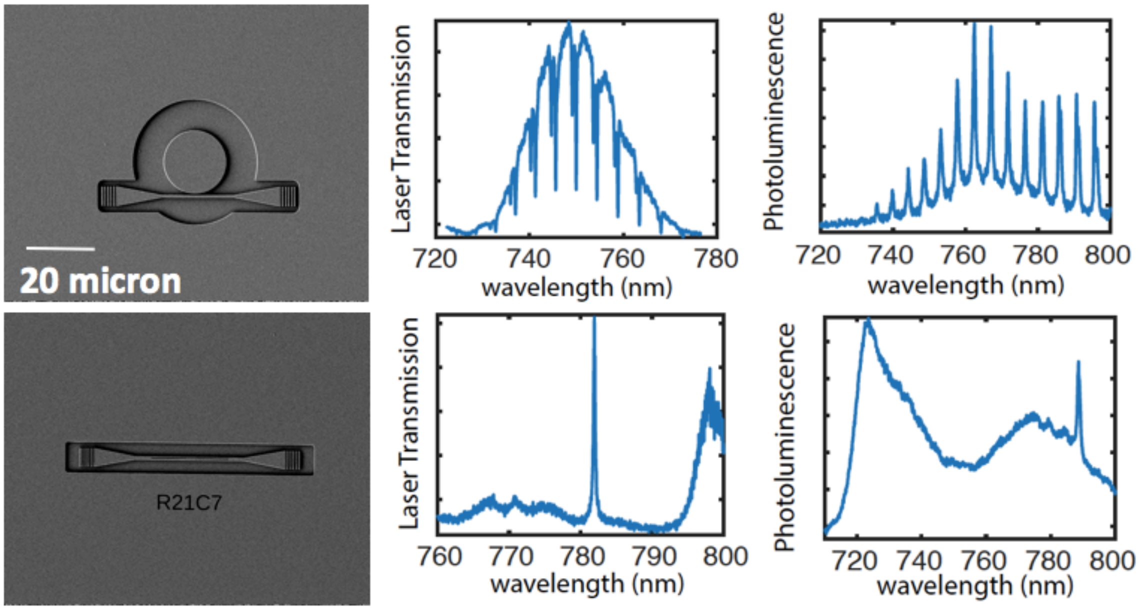

Figure 4: 2D material integrated silicon nitride devices: *Both disk resonator and nano-beam photonic crystal cavities were designed and fabricated in SiN. We measured the transmission and photoluminescence from the 2D material.*

Theoretical study of quasi phase matching in ring resonator by patterning 2D materials:

We theoretically analyze a new method to satisfy quasi-phase matching in nonlinear nanophotonics. In nano-cavities, the phase-matching condition for second-order nonlinear processes amounts to modal overlap between cavities at the fundamental and the harmonic frequencies. In existing material systems, the optimization of the cavities is difficult. Due to the extreme thinness of the 2D materials, the confined modes of the cavities remain unaffected with and without 2D materials. However, for a second-order nonlinear process, where the nonlinearity is primarily provided by the 2D materials, by patterning the 2D materials, a phse-matching can be obtained. The idea is, by spatial structuring of the 2D materials, the overall modal overlap can be engineered, unlike bulk materials, as the cavities are made of nonlinear materials. Hence, the patterning of the nonlinear optical materials changes the spatial distribution of the cavity modes. Thus, 2D materials provide a unique opportunity to perform phase-matching in hybrid nonlinear nanophotonics. Figure 5 shows the schematic of the devices, and simulation results. These results are currently being written up for a publication.

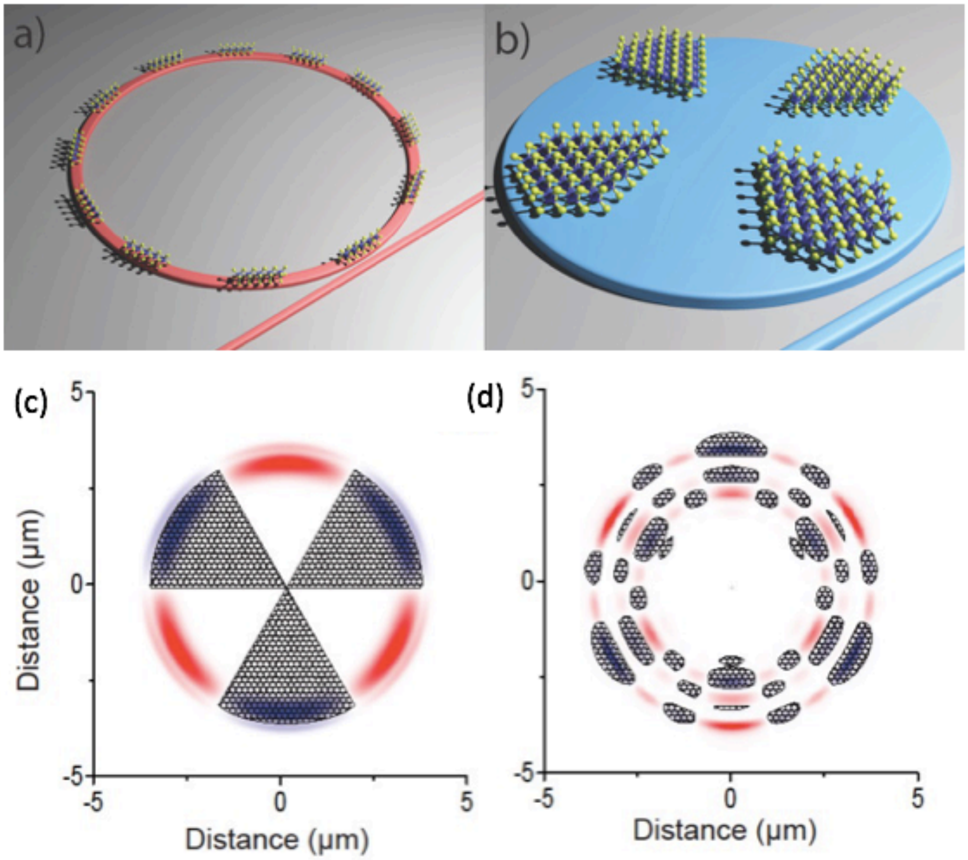

Figure 5: Patterning of 2D materials to enable phase matching in nonlinear nano-photonics: *Schematic of a (a) ring and (b) disk cavities with patterned 2D materials on top; (c), (d) Patterning of the 2D material on top of a disk for different modes.*

Developing graphene-SOI ring resonator platform for photo- detection and SEO devices: We aim to build a self-electro-optic (SEO) bistable platform using silicon photonics. At the heart of its operation is a cavity enhanced photo-detector, which we will realize using graphene. We have developed the fabrication flow for the device (Figure 6), and have optimized all the steps individually. We are now working on the whole process flow to fabricate the SEO devices. We have optimized the SOI fabrication process to get high Q resonances (Figure 7). We also have transferred the graphene on the SOI cavity, and developed a via process to electrically contact the graphene. We will continue research to fabricate the SEO device, and also the photo-detector.

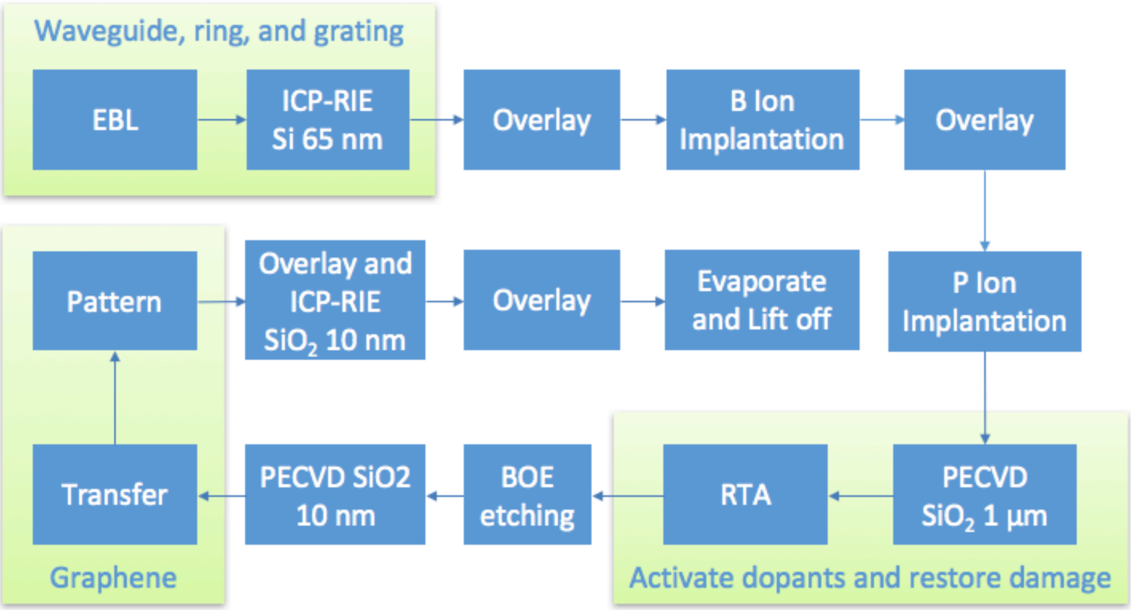

***Figure 6:** Fabrication flow for the Silicon SEO device*

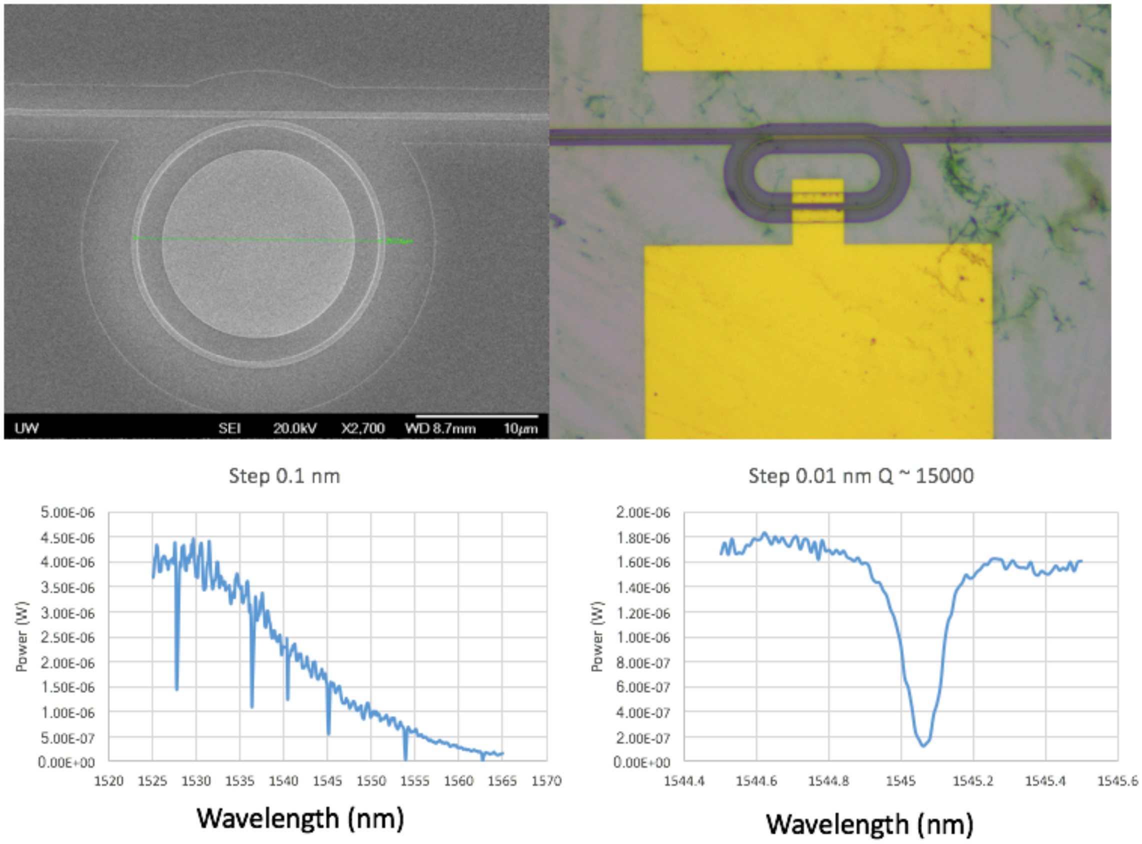

***Figure 7: Silicon devices:** SEM of the fabricated ring resonator and optical image of the ring with graphene on top, and the electrical circuits. The measured transmission spectrum of the ring resonator shows a quality factor exceeding 10,000.*

Encapsulated SiN cavity development and demonstration of 2D material coupling:

Most existing implementations of silicon nitride photonic crystal cavities rely on suspended membranes due to its low refractive index. Such floating membranes are not mechanically robust, making them suboptimal for developing a hybrid optoelectronic platform where new materials, such as layered 2D materials, are transferred onto pre-fabricated optical cavities. To address this issue, we design and fabricate a silicon nitride nanobeam resonator where the silicon nitride membrane is encapsulated by material with a refractive index of ~1.5, such as silicon dioxide or PMMA. The theoretically calculated quality factor of the cavities can be as large as 10^5, with a mode-volume of $\sim 2.5\left(\frac{\lambda}{n}\right)^3$. We fabricated the cavity and measured the transmission spectrum with the highest quality factor reaching 7,000. We also successfully transferred monolayer tungsten diselenide on the encapsulated silicon nitride nanobeam and demonstrated coupling of the cavity with both the monolayer exciton and the defect emissions.

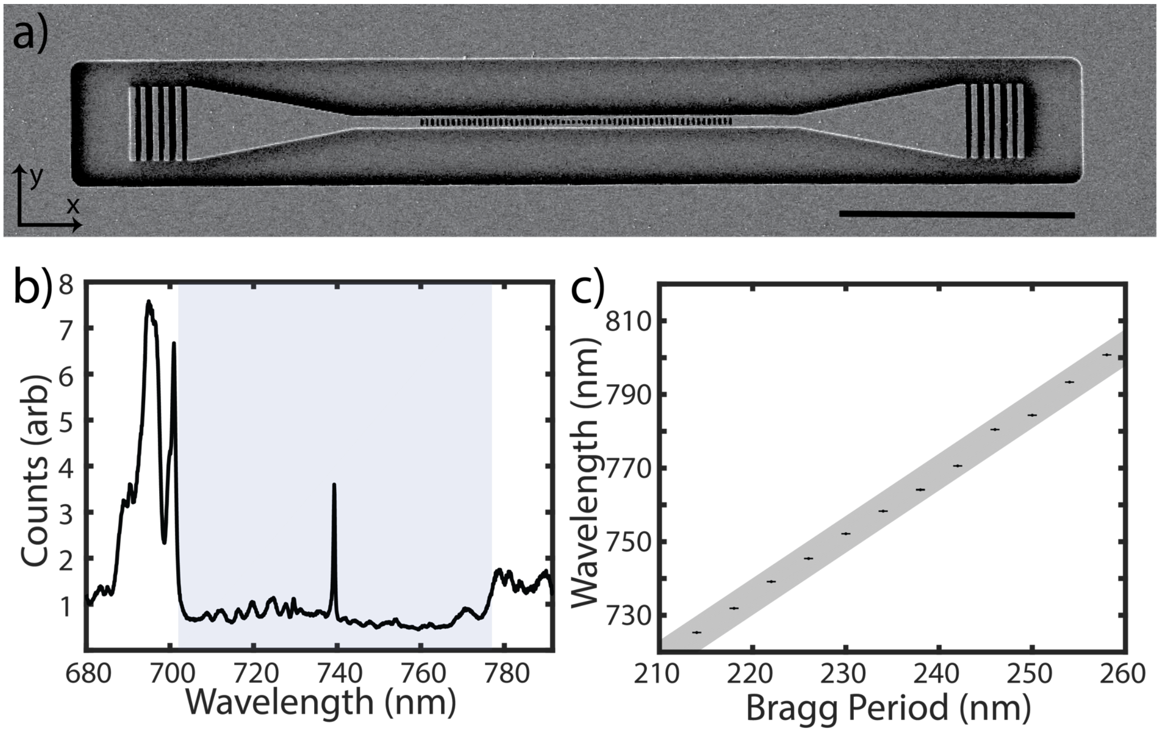

Figure 8: Bare cavity resonances: *(a) An SEM of a fabricated SiN nanobeam prior to encapsulation. The nanobeam resonators are probed via the two grating couplers on the ends of the nanobeams. The scale-bar is* 10 *μm. (b) Example cavity transmission spectrum as measured through the gratings. The shaded portion highlights the low transmission region from the Bragg reflectors, with the cavity peak at the center. (c) The observed cavity resonances scale linearly with the Bragg period, while holding the ratio between radii and periodicity constant.*

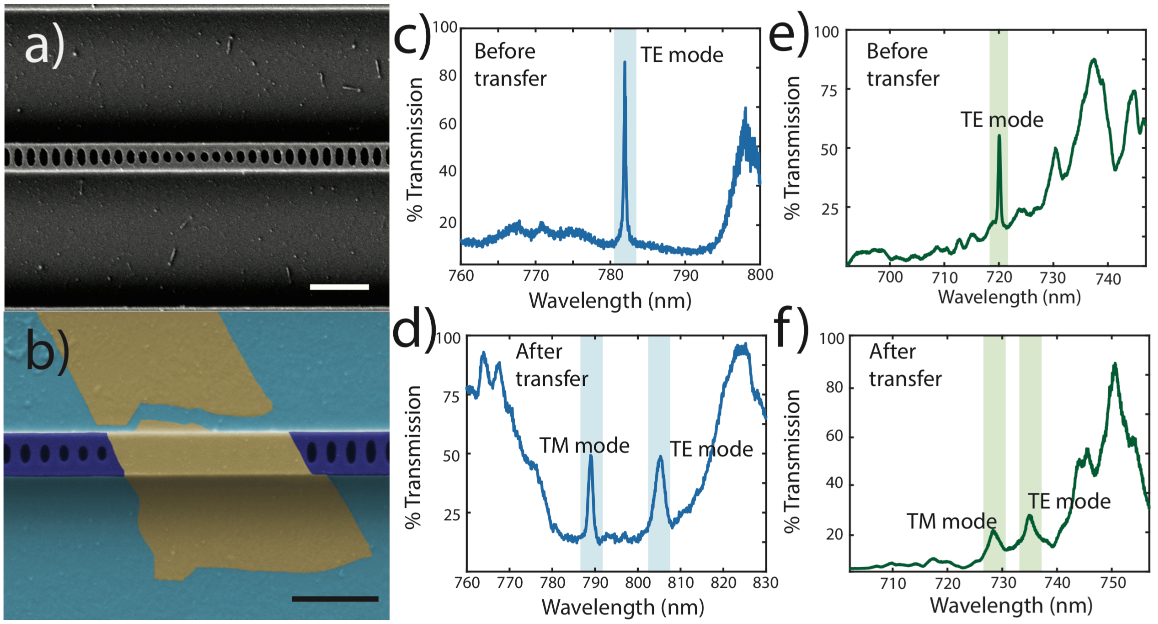

Figure 9: Transmission through SiN nanobeam before and after transfer of WSe_2: *(a) A SEM of the defect region of the nanobeam. (b) False colored SEM of a nanobeam with monolayer WSe_2. The SiN is shown in dark blue, the silicon oxide is shown in light blue, and the WSe_2 is shown in gold. The scale-bar in both figures corresponds to* $1\mu m$. *(c), (e) The transmission spectrum before transferring WSe_2 for devices 1 and 2, respectively. (d), (f) The transmission spectra after WSe_2 transfer for devices 1 and 2, respectively.*

References:

[1] K. F. Taylor, L. S. Kyle, Z. Jiajiu, L. Chang-Hua, X. Xiaodong, and M. Arka, "Silicon photonic crystal cavity enhanced second-harmonic generation from monolayer WSe 2," *2D Materials,* vol. 4, p. 015031, 2017.

[2] C.-H. Liu, G. Clark, T. Fryett, S. Wu, J. Zheng, F. Hatami, X. Xu, and A. Majumdar, "Nanocavity Integrated van der Waals Heterostructure Light-Emitting Tunneling Diode," *Nano Letters,* 2016/12/07 2016.

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Abstract

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2. Encapsulated silicon nitride nanobeam cavity for hybrid nanophotonics, Taylor K. Fryett, Yueyang Chen, James Whitehead, Zane Matthew Peycke, Xiaodong Xu, Arka Majumdar, ACS Photonics, 5 (6), pp 2176–2181 2018.

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