Department of Materials
Science and Engineering
UNIVERSITY OF WISCONSIN–MADISON

MSE 803: Quantum Materials and Devices (Fall 2021)

1) **Course Name and Number:** Quantum Materials and Devices, MSE 803
2) **Credits:** 3 credits
3) **Canvas Course URL:** https://canvas.wisc.edu/courses/264073
4) **Course Designations and Attributes:** *general education*

5) **Meeting Time and Location:**

   Lecture: MWF 11:00 - 11:50 am Engineering Hall 2309

6) **Instructional Mode:** In-person

7) **Credit Hour Definition:** Traditional Carnegie

8) **Instructors and Teaching Assistants**

   - Instructor Title and Name: Prof. Jun Xiao
   - Instructor Office Hours/Availability: WF 4:00-4:45 pm at ERB 729
   - Instructor Email/Preferred Contact: jun.xiao@wisc.edu
   - Teaching Assistant: N/A
   - TA Office Hours: N/A
   - TA Email/Preferred Contact: N/A

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9) Official Course Description

This course aims to introduce the fundamentals of quantum materials and a broad survey of their device applications. The experimental techniques to engineering solid-state quantum phenomena will also be covered. Graduate students and advanced undergraduate with required background are welcome to enroll.

10) Requisites

MS&E 456, ECE 466 or Physics 551

11) Learning Outcomes

a. **Course Learning Outcomes:**
After completing this course, students will be able to
- have a deep understanding and be familiar with essential concepts of quantum materials and devices for related literature reading and future lab research.
- design quantum materials and devices by various engineering approaches
- identify available quantum research resource on campus and catalyze potential research collaboration and quantum science related job applications

b. **Abet Student Outcomes:**
- an ability to apply knowledge of mathematics, science, and engineering
- an ability to design and conduct experiments, as well as to analyze and interpret data
- an ability to identify, formulate, and solve engineering problems
- the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context
- a recognition of the need for, and an ability to engage in life-long learning
- a knowledge of contemporary issues
- an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

12) Brief List Of Topics To Be Covered

Quantum mechanics, band theory, low-dimensional quantum materials, topological insulators and semimetals, metal-insulator transition, superconductivity, quantum devices, light-matter interactions

13) Discussion Sessions
TBD

14) Grading

Problem sets	40%
Participation	10%
Final project	50%

4 problem sets will be assigned every 3 or 4 weeks. Each problem set needs to be finished and submitted through Canvas within two weeks after its release. **The final project** will be a short paper (25%) + presentation (20%) on a current research topic in quantum materials and devices, due on the date of the final exam period (Dec 17). The presention topic should be identified by Nov 10th

(5%). Presentations will take place during the last weeks of class. More details to follow in the class.

15) Recommended Reading

The course topic is brand new and no textbook is required. Below are recommended readings from excerpts of books and journals, in addition to class notes.

Books:

Solid State Physics: An introduction, by Hofmann [online @ UW library]

Electronic Properties of Materials, by Rolf Hummel [online @ UW library]

Semiconductor Photonics of Nanomaterials and Quantum Structures, by Arash Rahimi-Iman [online @ UW library]

Journal papers:

1. Manna K, Sun Y, Muechler L, Kubler J, Felser C (2018) Heusler, Weyl and Berry. Nature Reviews Materials, 3, 224-256. https://doi-org/10.1038/s41578-018-0036-5

2. Hasan MZ, Kane CL (2010) Colloquium: Topological insulators. *Reviews of Modern Physics*, 82(4):3045–3067. https://doi.org/10.1103/RevModPhys.82.3045

3. Aharonovich I, Englund D, Toth M (2016) Solid-state single-photon emitters. *Nature Photonics*, 10(10):631–641. https://doi.org/10.1038/nphoton.2016.186

4. Schirhagl R, Chang K, Loretz M, Degen CL (2014) Nitrogen-Vacancy Centers in Diamond: Nanoscale Sensors for Physics and Biology. *Annual Review of Physical Chemistry*, 65(1):83–105. https://doi.org/10.1146/annurev-physchem-040513-103659

5. Basov DN, Averitt RD, Hsieh D (2017) Towards properties on demand in quantum materials. *Nature Materials* 16, 1077-1088. https://doi-org /10.1038/nmat5017

6. Giustino et al. (2021), The 2021 quantum materials roadmap. *J. Phys. Mater.* 3, 042006. https://doi.org/10.1088/2515-7639/abb74e

7. Liu X, Hersam M (2019). 2D materials for quantum information science. *Nature Reviews Materials* 4, 669. https://doi.org/10.1038/s41578-019-0136-x

8. Gilbert, M (2021). Topological electronics. *Communications Physics* 4, 70. https://doi.org/10.1038/s42005-021-00569-5

9. Liu C et al. (2020). Two-dimensional materials for next-generation computing technologies. *Nature Nanotechnology* 15, 545. https://doi.org/10.1038/s41565-020-0724-3

There may be additional readings recommened in class.

16) **Contents**

1. Introductory Remarks

1.1 Perspective: Quantum materials and devices for quantum technologies
overview of pre-requisite knowledge, lecture contents, and assignments

1.2 Crystal structure and symmetry: periodic lattice, reciprocal space, symmetry, and defects

1.3 Band theory of solids: review of basic concepts in quantum mechanics, Bloch wave, band structure, density of states, and quasiparticles

2. Low-dimensional quantum materials

2.1 Quantum confinement

2.2 Van der Waals materials and their optoelectronic properties

2.3 Color centers in solids, Quantum dots and single-photon sources

3. Topological quantum materials

3.1 Topology and Berry phase in solids

3.2 Topological insulators and their device applications

3.3 Dirac, Weyl semimetals and their device applications

3.4 On-demand topological band engineering

4. Correlated quantum materials arising from many-body interactions

4.1 Band theory limitation and electron correlation

4.2 Metal-insulator transitions, Mott insulator, Mottronics, Magnetism, spintronics, Light-driven electronic phase transitions

4.3 Superconductivity, Josephson junction and superconducting qubits

5. Challenges and opportunities in quantum science and technology
(guided critical and creative thinking practice session)

17) **Tentative Schedule:** (3 lectures/week, MWF 11:00 – 11:50 am)

Topic	Date
1.1 Course topics and methodology overview	Sept 8, 10
1.2 Crystal structure and symmetry	Sept 13, 15, 17
1.3 Band theory of solids	Sept 20, 22, 24, 27, 29
HW 1	
2.1 Quantum confinement	Oct 1, 4
2.2 Layered materials and heterostructures	Oct 6, 8, 11, 13, 15, 18
2.3 color centers, quantum light sources and sensing	Oct 18, 20, 22
HW 2	
3.1 Topology and Berry phase	Oct 25, 27
3.2 Topogical insulators and devices	Oct 29, Nov 1, 3
3.3 Topological semimetals	Nov 5, 8, 10
3.4 Topological band engineering	Nov 12, 15
HW 3	
4.1 Electron correlation	Nov 17, 19
4.2 Metal-insulator transitions	Nov 22, 24, 29
4.3 Superconductivity, superconduting qubits	Dec 1, 3, 6
HW 4	
5 Outlook for quantum science and technology (critical/creative thinking practice)	Dec 8
Final project presentation	Dec 10, 13, 15
Final project paper due	Dec 17