Academic Year	AY19/20	**Semester**	2
Course Coordinator	Asst/Prof Bent WEBER		
Course Code	PH4404		
Course Title	Nanoscale Physics		
Pre-requisites	PH3101 Quantum Mechanics II and PH3102 Condensed Matter Physics I		
No of AUs	3AU		
Contact Hours	Face to face: 3 hours a week (2h lecture each week, 1h tutorials every fortnight, 1h seminars every fortnight)		
Proposal Date	06 December 2019		

Course Aims

This course is targeted at physics students in their fourth year. It aims at introducing how quantum mechanical behavior emerges in condensed matter systems at the nanometer scale, and how quantum mechanical laws govern their properties. The course will provide an overview of physical phenomena that are observed experimentally, introduce their underlying physical principles, and aims to build the analytical skills to describe these phenomena mathematically. This course thus will equip you with the relevant concepts of modern nanoscience and technology that will prepare you to follow or initiate research in field or to work in industry jobs related to applied nanoscience and technology.

Intended Learning Outcomes (ILO)

Upon successful completion of this course, you should **be able to:**

History of Nanoscience and Technology (HIS)

1. Provide an overview of modern nanoscience and technology and have a good grasp of their key milestones

Basics of nanoscale science (BAS)

1. Use basic quantum mechanical formalism, such as the time-dependent and time-independent Schrodinger equation in free space, to calculate charge and current densities.
2. Use basic condensed matter concepts to calculate/derive the density of states in 1D, 2D, and 3D, as well as local density of states.
3. Use occupation functions to calculate the density of occupied electronic states and Fermi level
4. (Quantitatively) explain the formation bands and bandgaps, as well as electronic states based on Bloch functions, and electrons motion based on effective electron mass.
5. Distinguish metals from semiconductors based on band structure, as well as distinguish direct from indirect band gaps.
6. Describe crystal structure in terms of lattice vectors and reciprocal space in terms of reciprocal and construct Brillouin zones for in different dimensions and for different crystal structures.

Introduction to low dimensional structures (LD)

1. Classify low-dimensional electronic structure by dimensionality (2D and 1D electron gasses, nanowires, quantum dots).
2. Describe heterostructure engineering in semiconductors by different methods, such as molecular beam epitaxy, physical, and chemical vapour deposition, etc.
3. Classify different types of band alignment and how it can leads to the formation of 2DEGs by band engineering, compositional control and doping.
4. Describe more complex heterostructures, such as resonant tunnelling diodes, and superlattices
5. Explain the basic assumptions of effective mass theory (and its limitations) and how it allows to calculate electronic structure based on envelope functions.

Quantum wells and low-dimensional systems (QW)

1. Solve the time-independent Schrodinger equation for different confinement potentials and in different dimensions, such as infinite and finite square wells, parabolic, triangular, and Coulombic wells in 1D, 2D and 3D.
2. Calculate subband structure and density of states for different confinement potentials, and calculate subband occupation.

Tunneling transport (TT)

1. Solve the time-dependent Schrodinger equation at for spatial potential profiles (steps, barriers, wells) using proper wave function matching conditions, and express the results using transmission and reflection amplitudes.
2. Use the T-Matrix formalism to calculate transmission across steps, potential barriers and double barriers.
3. Calculate current and conductance from transmission
4. Describe transmission for systems with many channels, many leads, or both in the context of the Landauer-Buttiker formalism.

Electric and magnetic fields (EM)

1. Distinguish between different gauges and gauge transformations, and how they affect the interpretation of the solution to the Schrodinger equation.
2. Solve the time-dependent Schrodinger equation, considering both scalar and vector potentials, in electric and in magnetic fields for Landau or symmetric gauge.
3. Derive the formation of Landau levels, and understand their dependence on magnetic field and calculate their filling factor
4. Explain how the integer quantum Hall effect arises in a magnetic field, and how edge states arise in a 2DEG.
5. Calculate the period in the transmission across an Aharonov-Bohm interferometer.

Course Content

Basics of nanoscale science (BAS)	Review of basic QM: time dependent and time independent Schrödinger equation, charge and current density; Review of semiconductor physics in various dimensions: density of states and local density of states, occupation functions and density of occupied states, free electron gas, Fermi energy, doping, crystal structure and band structure, phonons.
Introduction to low dimensional structures (LD)	Heterostructures and their growth methods, band engineering, other low-dimensional structures (nanowires, quantum dots, carbon nanotubes, graphene); effective mass approximation
Quantum wells and low-dimensional systems (QW)	Square, parabolic, and triangular wells, subbands and their occupation, notable confining potentials in 2D and 3D, quantum wires and quantum dots (Coulomb blockade and Kondo effect)
Tunneling transport (TT)	Potential steps and barriers, transfer matrices, double barrier and resonant tunneling, current and conductance, resonant tunneling diodes, superlattices and minibands, systems with many channels, systems with many leads (Landauer and Landauer-Büttiker equations)
Electric and magnetic fieldsm (EM)	Schrödinger equation with electric and magnetic fields, uniform electric field (Franz-Keldysh effect, Bloch oscillations, Stark localization, quantum confined Stark effect), uniform magnetic field (Landau levels, classical and quantum Hall effects, Shubnikov-de Haas effect, de Haas-van Alphen effect, Aharonov-Bohm effect)

Assessment (includes both continuous and summative assessment)

Component	Course ILO Tested	Related Programme LO or Graduate Attributes	Weighting	Team/Individual	Assessment rubrics
1. Final Exam	All	Competency (1,3,4)	50%	Individual	Point-based marking (not rubric based)
2. CA1: Reading Project “Topics in Nanoscale Physics” (report and presentation)	Depending on individual project topic (ILO BAS to EM)	Competency (1,4,5), Communication (1,2,3), Character (1,2,3)	15%	Team* (2 – 3 students, depending on class size)	Rubrics based marking (see appendix)
3. CA2 weekly homework	All	Competency (1,3,4)	10%	Individual	Point-based marking (not rubric based)
4. CA3: Midterm exam	BAS to TT	Competency (1,3,4)	25%	Individual	Point-based marking

					(not rubric based)
Total			*100%*		

*There can be individual variation of marks within a team, depending on the evaluation by the lecturer, or feedback from the peers, should individual students' participation in the group be subpar.

Formative feedback

Formative feedback is given weekly through assignments marking and tutorial lessons. A weekly TA meeting discusses the progress, pace, and difficulty level of lectures. Formative feedback on the midterm exam is given as a midterm check of students' understanding of learned contents, including feedback on common mistakes. Past exam questions and examiner's report are made available for students. Finally, your lecturer will try and make himself available for fast turn-around feedback on a one-on-one basis, through email or personal discussions after lecture, tutorials, or during consultation.

Learning and Teaching approach

Approach	**How does this approach support you in achieving the learning outcomes?**
Lectures	Content and derivations, examples of problem solving and discussion of conceptual understanding.
Tutorial	Review and discussion of key concepts from lectures with TAs, by working through problems. The TAs will monitor and provide timely feedback.
Homework	Homework comprises standard textbook practice questions that are covered during tutorials allowing for formative assessment and feedback.
Project (team)	Team-based reading project based on group work (2-3 students based on class size). You will research a specific topic (either chosen by you as a group, or suggested by the lecturer), and you will communicate your research to your peers in writing (report) and group presentation. The presentations will be held towards the end of the course during lecture / tutorial hours.

Reading and References

- Davies, The Physics of Low-Dimensional Semiconductors: An Introduction, Cambridge University Press (**ISBN-10:** 052148491X; **ISBN-13:** 978-0521484916)
- Datta, Electron Transport in Mesoscopic Systems, Cambridge University Press (**ISBN-10:** 1107605288; **ISBN-13:** 978-1107605282)
- Ferry/Goodnick, Transport in Nanostructures, Cambridge Univ. Press (**ISBN-13**: 978-0521877480; **ISBN-10**: 0521877482)

Course Policies and Student Responsibilities

Absence Due to Medical or Other Reasons

If you are sick and unable to attend your class / Mid-terms, you have to:

1. Send an email to the instructor regarding the absence and request for a replacement class and make-up mid-terms.
2. Submit the original Medical Certificate* or official letter of excuse to administrator.
3. Attend the assigned replacement class (*subject to availability*) and make-up mid-terms.

* The medical certificate mentioned above should be issued in Singapore by a medical practitioner registered with the Singapore Medical Association.

Academic Integrity

Good academic work depends on honesty and ethical behaviour. The quality of your work as a student relies on adhering to the principles of academic integrity and to the NTU Honour Code, a set of values shared by the whole university community. Truth, Trust and Justice are at the core of NTU's shared values.

As a student, it is important that you recognize your responsibilities in understanding and applying the principles of academic integrity in all the work you do at NTU. Not knowing what is involved in maintaining academic integrity does not excuse academic dishonesty. You need to actively equip yourself with strategies to avoid all forms of academic dishonesty, including plagiarism, academic fraud, collusion and cheating. If you are uncertain of the definitions of any of these terms, you should go to the academic integrity website for more information. Consult your instructor(s) if you need any clarification about the requirements of academic integrity in the course.

Collaboration is encouraged for your homework because peer-to-peer learning helps you understand the subject better and working in a team trains you to better communicate with others. As part of academic integrity, crediting others for their contribution to your work promotes ethical practice.

You **must write up your solutions by yourself and understand anything that you hand in.**

If you do collaborate, **you must write on your solution sheet the names of the students you worked with. If you did not collaborate with anyone, please explicitly write, "No collaborators."** Failure to do so constitutes plagiarism.

Use of materials outside the course is strongly discouraged. If you use outside source, you must reference it in your solution.

Course Instructors

Instructor	Office Location	Phone	Email
Asst/Prof Bent Weber	SPMS-PAP-05-01b	8261 0508	b.weber@ntu.edu.sg

Planned Weekly Schedule

Week	Topic	Course ILO	Readings/ Activities

1	Lecture 0 (2h): Plenty of Room at the Bottom – Introduction to Nanoscience and Technology Lecture 1 (1h): QM formalism, charge and current densities, densities of states	**HIS** **BAS** 1-2	Textbook, article "There's plenty of room at the bottom" (Richard P. Feynman), video
2	Lecture 2 (2h): Occupation functions / Fermi level Tutorial 1 (1h)	**BAS** 3 – 4	Textbook
3	Lecture 3 (2h): Electronic bands 1D and 2D Lecture 4 (1h): Electronic bands 3D, band engineering and semiconductor manufacturing	**BAS** 5 – 6 **LD** 1 - 4	Textbook
4	Lecture 5 (2h): Effective mass approximation Tutorial 2 (1h)	**LD** 5	Textbook
5	Lecture 6 (2h): Quantum wells in 1D (Part I + II) Lecture 7 (1h): Density of states and subbands	**QW** 1	Textbook
6	Lecture 8 (2h): 2D and 3D confining potentials Tutorial 3 (1h)	**QW** 2	Textbook
7	Lecture 9 (2h): Tunneling Transport (Part I and II): Potential steps and T-matrix formalism Lecture 10 (1h): Tunneling Transport (Part III): Transmission across a double-barrier	**TT** 1 **TT** 2	Textbook
Recess Week			
8	Lecture 11 (2h): Tunneling Transport (Part IV): Current and Conductance Tutorial 4 (1h)	**TT** 3	Textbook
9	Lecture 12 (2h): Tunneling Transport (Part V): Landauer formula and Landauer-Buttiker formalism Lecture 13 (1h): Tunneling Transport (Part VI): Landauer formula and Landauer-Buttiker formalism	**TT** 4 **TT** 4	Textbook
10	Lecture 14 (2h): Electric and Magnetic Fields in QM (Parts I and II) Tutorial 5 (1h)	**EM** 1 - 2	Textbook
11	Lecture 15 (2h): Magnetic fields (Part I) Lecture 16 (1h): Magnetic fields (Part II)	**EM** 1 - 2 **EM** 3 - 5	Textbook
12	Lecture 17 (2h): Student presentations Tutorial 6 (1h): Student presentations	**BAS** to **EM** (depending on topic)	Textbook

13	Lecture 17 (2h): Student presentations Lecture (1h): Revision (recap of key concepts)	**BAS** to **EM** (depending on topic)	Textbook
Examination Week			

Appendix A

Appendix: Rubrics

Project Report (Adapted from https://www.cte.cornell.edu/documents/Science%20Rubrics.pdf), adapted to include ideas of SOLO taxonomy)

Criteria	**Does not meet standard (0 - 2) (Prestructural)**	**Nearly Meets Standard (3 – 4) (Unistructural)**	**Meets Standard (5 - 6) (Multistructural)**	**Exceeds Standard (7 - 8) (Relational)**	**Far Exceeds Standard (9 - 10) (Extended Abstract)**
Problem or Research Statement	Unclear and inaccurate or illogical statement.	Somewhat unclear or unable to accurately portray the problem.	Mostly clear and accurately communicated for the focused reader.	Clearly and accurately communicated, and gives most background or context and motivation.	Comprehensive description and overview of the topic, satisfactory to the expert reader.
Correctness and appropriate description of the physics	Incorrect or inappropriate use of physics in most areas.	Mostly correct and appropriate use of physics. But flawed in parts.	Correct and appropriate use of physics, with some clarity on assumptions, approximations, experimental techniques, and derivations.	Correct and appropriate use of physics, with assumptions, approximations, experimental techniques, and derivations that are accurate and detailed.	Correct and appropriate use of physics, with assumptions, approximations, experimental techniques, and derivations that are accurate and detailed. With further details of their limitation and how these could be improved.
Development of Ideas	Does not clearly introduce the topic. Does not establish or maintain focus on the topic.	Introduces the topic. Somewhat maintains focus on the topic, but lost in some parts. Development of some of the ideas.	Introduces the topic clearly. Maintains focus on the topic. Development of and/or connection between ideas are clear and correct.	Introduces the topic clearly and creatively. Maintains clear focus on the topic throughout. Development of and connection between ideas are clear and correct.	Introduces the topic clearly and creatively. Maintains clear focus on the topic throughout. Development of and connection between ideas are clear and correct. Gives detailed outlook on how ideas could be further developed in the future.
Use of secondary material (references and citations)	Improper and unclear citations and attribution of others' work in most part, and with major errors.	Partly proper and clear citations and attribution of others' work, with some errors.	Proper, accurate and clear citations and attribution of others' work in most parts.	Proper, accurate and clear citations and attribution of others' work throughout.	Proper, accurate and *complete* referencing and attribution of others' work in the field.

Project Presentation

Criteria	**Does not meet standard (0 - 2) (Prestructural)**	**Nearly Meets Standard (3 – 4) (Unistructural)**	**Meets Standard (5 - 6) (Multi-structural)**	**Exceeds Standard (7 - 8) (Relational)**	**Far Exceeds Standard (9 - 10) (Extended Abstract)**
Organization and structure	No clear structure apparent to the presentation. Ideas appear scattered and incoherent. No clear distinction between introduction of background concepts, presentation of main results, and conclusions.	Somewhat structured presentation. Distinct sections such as introduction, results, conclusions, etc. exist, but sections are incomplete and their content scattered / unstructured.	Structured presentation. Distinct sections such as introduction, results, conclusions, etc. exist, and their content is mostly organized. Key conclusions are only apparent after reading the conclusions slide.	Well-structured presentation. Distinct sections such as introduction, results, conclusions, etc. exist, their content is well-organized throughout the presentation, and the key conclusions are clear throughout.	Above standard structured presentation. Content of introduction, results, conclusions, etc. are well organized throughout the entire presentation, presenting content not only comprehen-sively, but efficiently.
Visual presentation (e.g. design of presentation slides)	Ineffective or no use of presentation technology (e.g. PowerPoint) at all.	Somewhat effective use of presentation technology (e.g. PowerPoint slides). Technology is used but content presented is mostly illegible and disorganized	Effective use of technology (e.g. PowerPoint slides). Information legible and well-organized throughout most of the presentation.	Effective use of technology (e.g. PowerPoint slides). Information legible and well-organized throughout the entire presentation.	Effective and creative use of technology (e.g. PowerPoint slides). Information is not legible but also well-structured. Additional technology / applets (e.g. PPT animations are being used to further illustrate complex concepts.
Effectiveness of oral presentation and Q&A	Does not communicate ideas effectively. Uses pace, tone and style ineffectively (monotonous style) and hence loses attention of audience through most of the presentation.	Communicates ideas somewhat effectively. Ideas are are mostly comprehensiblea nd communicated somewhat effectively by use of pace, tone and style. Maintains attention of audience in some parts of the presentation.	Communicates ideas in an effective and understandable manner. Uses pace, tone and style effectively, most of the time. Catches the interest of the audience through most of the presentation	Communicates difficult or complex ideas in an effective and understandable way. Uses pace, tone and style effectively all the time, and catches the interest of the audience, or engages the audience throughout	Far exceeds expectations of a fourth year student in communicating complex scientific concepts. Uses pace, tone and style not only effectively but also creatively. Never loses interest and engagement of the audience
Individual Contribution	Little to no effective contribution in the presentation and Q&A portions, displays	Contribution in the presentation and Q&A portions reflect only one aspect the chosen	Contribution in the presentation and Q&A portions reflect more than one aspect of the chosen topic, but	Contribution in the presentation and Q&A portions reflect depth of knowledge not only in an	Contribution in the presentation and Q&A portions reflect coherence, fluency, and depth of knowledge in the

	little knowledge in the chosen topic.	topic. Limited insights.	does not connect them as a coherent whole. Insights may be unoriginal.	individual segment, but in the whole topic. Insights are thoughtful and analytical.	whole topic. Comes across as an integral part of the team. Insights are critical and offer new or unique perspectives on the topic.

The main presentation should include:
• a ***presentation*** of the appropriate ***concepts, theories and principles*** of the problem
• an ***explanation*** of the ***observed phenomena***
• an ***application*** of ***appropriate mathematics***
• reasonable **experimental technique** to ***gather*** and ***record data*** (or ***demonstrate*** the ***phenomena*** if appropriate)
• linking of ***theoretical*** and ***experimental findings*** to draw ***suitable conclusions***
• an attempt to communicate ***difficult*** or ***complex*** ideas in an ***effective*** and ***understandable*** manner

Student participation:
All students in the team need to participate in the presentation or Q&A, as the report and presentation will be a team assessment (in principle) so that it is possible to give a grade for each student.

Duration: Presentation (10-15 min) + Q&A (5 min) = Total of 20 min.

What we want our graduates from Physics and Applied Physics to be able to do:

Upon the successful completion of the PHY, APHY and PHMA programs, graduates should be able to:

Competency	1	demonstrate a rigorous understanding of the core theories and principles of physics involving (but not limited to) areas such as classical mechanics, electromagnetism, thermal physics and quantum mechanics [PHMA only] demonstrate a rigorous understanding of the core theories and principles of mathematical sciences involving (but not limited to) areas such as analysis, algebra and statistical analysis
	2	read and understand undergraduate level physics content independently;
	3	make educated guesses / estimations of physical quantities in general;
	4	apply fundamental physics knowledge, logical reasoning, mathematical and computational skills to analyse, model and solve problems;
	5	develop theoretical descriptions of physical phenomena with an understanding of the underlying assumptions and limitations;
	6	critically evaluate and distinguish sources of scientific/non-scientific information and to recommend appropriate decisions and choices when needed;
	7	demonstrate the ability to design and conduct experiments in a Physics laboratory, to make measurements, analyse and interpret data to draw valid conclusions.

Creativity	1	propose valid approaches to tackle open-ended problems in unexplored domains;
	2	offer valid alternative perspectives/approaches to a given situation or problem.

Communication	1	describe physical phenomena with scientifically sound principles;
	2	communicate (in writing and speaking) scientific and non-scientific ideas effectively to professional scientists and to the general public;
	3	communicate effectively with team members when working in a group.

Character	1	uphold absolute integrity when conducting scientific experiments, reporting and using the scientific results;
	2	readily pick up new skills, particularly technology related ones, to tackle new problems;
	3	contribute as a valued team member when working in a group.

Civic Mindedness	1	put together the skills and knowledge into their work in an effective, responsible and ethical manner for the benefits of society.