Quantum Computing and Information Specialization in Electrical Engineering Master Degree

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***Abstract*—In this paper, we discuss the Quantum Computing and Information (QCI) Specialization introduced in Fall 2021 in the Department of Electrical Engineering at San Jose State University (SJSU). SJSU is a Minority and Hispanic Serving Institution at the heart of Silicon Valley. Its engineering graduates have been the major workforce supply in the semiconductor industry in the last few decades. As quantum technology is becoming more and more prominent in the industry, it is important to train the students to be quantum-aware. In the course of developing quantum technology classes, the balance needs to be taken by considering the education and social-economic backgrounds of the students and the "return-on-investment" (ROI) from both the student and school resource perspectives. Therefore, to achieve the balance, a QCI specialization was introduced with three classes, namely, Introduction to Quantum Computing, Cryogenic Nanoelectronics, and Quantum Computing Architectures. We will discuss the design of the courses and how they provide the minimal knowledge engineering students need to learn to work in the quantum technology industry.**

Keywords—Introduction to Quantum Computing, Cryogenic Nanoelectronics, Quantum Education, Quantum Computing Architectures

I. Introduction

For decades, non-PhD Minority Serving Institutions (MSI's) have been steadily providing a diverse workforce to the semiconductor industry, which sustains the US semiconductor industry's ecosystem and its competitiveness. For example, some Silicon Valley companies, such as Apple and Cisco, hire the most alumni from San Jose State University (SJSU) as test engineers, circuit and layout designers, device engineers, programmers, marketing and program managers, business analysts, lawyers, etc. [1]. This is also a result of the close collaboration between SJSU and the industry on internship and certificate programs. Similarly, we believe, for US Quantum Computing (QC) industry and ecosystem to be successful and competitive, a diverse workforce with QC know-how from MSI is not just crucial but essential. While the core technologies such as quantum qubits, sensors, and interconnect are critical, the design and testing of cryogenic digital/analog circuits/systems for the QC periphery are also indispensable for the success of the QC industry. Therefore, the workforce should be trained not only on the core technologies but also on the peripheries, which have been supported very well by MSI graduates in the semiconductor era.

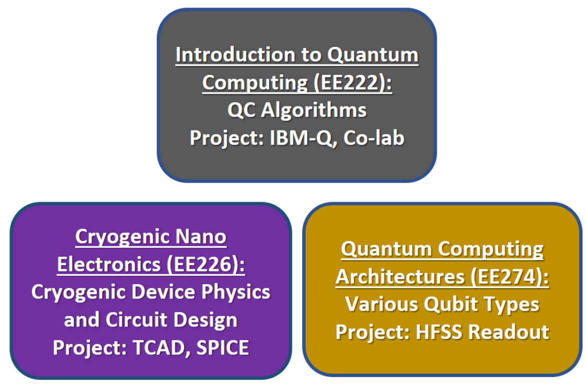

Figure 1: The three classes for EE Master Degree Quantum Computing and Information Specialization at San Jose State University.

There are a few obstacles for non-PhD MSI to overcome in order to achieve the goal. 1) Many MSI students are of socioeconomically disadvantaged. They are less prepared academically to study QC. They are also less motivated to participate in this new but "not-yet-profitable" industry. 2) MSI is less prepared financially to purchase expensive cryogenic equipment and hire instructors in this nascent area. Lacking Ph.D. student teaching assistants as class tutors in non-PhD MSI also impedes the students from understanding advanced topics better. As a result of this vicious cycle, fewer students and instructors who are interested in QC will join MSI.

In the Department of Electrical Engineering at SJSU, we designed a Quantum Computing and Information (QCI) Specialization for the master degree with 3 classes, namely, Introduction to Quantum Computing (EE225), Cryogenic Nanoelectronics (EE226), and Quantum Computing Architectures (EE274) to train quantum-aware engineers to solve this problem (Fig. 1). This strives to be the minimal investment required by the engineering students to enter the quantum technology industry.

The following sections discuss the three classes followed by discussions and conclusions.

TABLE I. FALL TEACHING SCHEDULE OF INTRODUCTION TO QUANTUM COMPUTING (EE225)

Week	Class	Seminar
1	1	Basic Mathematics and Quantum Mechanics
	2	Basic Mathematics and Quantum Mechanics
2	3	Basic Mathematics and Quantum Mechanics
	4	Basic Mathematics and Quantum Mechanics
3	5	Labor Day – No Class
	6	Basic Mathematics and Quantum Mechanics
4	7	Quantum Bits, Gates and Circuits
	8	Quantum Bits, Gates and Circuits
5	9	Quantum Bits, Gates and Circuits
	10	Quantum Bits, Gates and Circuits
6	11	Quantum Bits, Gates and Circuits
	12	Measurement
7	13	Measurement
	14	Teleportation
8	15	Teleportation
	16	Review
9	17	Midterm
	18	Deutsch's Algorithm
10	19	Deutsch's Algorithm
	20	Grover's Algorithm
11	21	Grover's Algorithm
	22	Encryption and Shor's Algorithm
12	23	Encryption and Shor's Algorithm
	24	Encryption and Shor's Algorithm
13	25	Encryption and Shor's Algorithm
	26	Physical Qubits
14	27	Physical Qubits
	28	Non-Instructional Day
15	29	Physical Qubits
	30	Physical Qubits
16	31	Review

II. INTRODUCTION TO QUANTUM COMPUTING (EE225)

While it will be fruitful to teach the students the hard-core theories of quantum technology [2][3], it is very difficult to make this into an effective first course for disadvantaged or less-prepared students. This is because every quantum technology topic is very profound and most disadvantaged students will not have time after classes to further understand the concepts. This will further enhance the equity gap, i.e. they will feel again they are lagging in front of the fancy and possibly very profitable future careers because they don't have the resources to study more after class. As we know, disadvantaged students are usually discouraged because they think that they "cannot do". If an introductory course is too deep and thus we have no time to transfer the skill/knowledge to them, we will only discourage them more and the first class can then be their last class in Quantum Information Science and Engineering (QISE).

In our Introduction to Quantum Computing class, we set the standard reasonable but try to make each step very concrete (even keep repeating) and hold their hands step by step to make sure they understand every step and can reproduce themselves (note that there is no class TA in SJSU). The goal is that, at the end of a semester, they can understand Shor's algorithm (only the factorization part) to the level that they understand how each qubit evolves in the circuit and can do this with hand calculation/ python programming/ IBM-Q. The course material is developed by working backward to find out the minimal set of knowledge we need to teach to achieve this goal. It is done until matrix multiplication.

In the process, we need to guide them psychologically so that they only learn the rules and are not distracted by concepts and philosophy. They learn bra-ket notation and operations like how the elementary school students learn multiplication and division without really understanding the reason (which they don't need to). They only need to master the skill.

Being able to do so, QISE can then be demystified and they understand why QISE is so powerful (due to superposition, entanglement, interferences) and its limitations. This is very important to help them set their feet on the ground in the first class. This is very beneficial for underprepared and disadvantaged students.

Table I shows the Syllabus of EE225. The students learn linear algebra by using quantum computing examples in the first few classes. By using the step-by-step approach as in [4], students are able to understand more advanced algorithms after the class (e.g. a student was able to understand HHL and apply it to research problems in [5] and [6]). A student who has self-studied using the recorded class videos was also able to perform an advanced analysis of the HHL algorithm [7].

In this class, IBM-Q [8] is used to execute quantum programs and the students are required to use python in Google Co-lab to simulate Grover's Algorithm.

III. CRYOGENIC NANOELECTRONICS (EE226)

Electrical engineering students have good training in device physics and circuit design. They are expected to contribute to the quantum computing industry easily by working on the periphery circuit designs. Therefore, Cryogenic Nanoelectronics EE226 is designed to help them understand the device and circuit behaviors at cryogenic temperature (4.2K).

Table II shows the syllabus of EE226. Students will learn the device behavior of bulk MOSFET, FinFET, and SOI at cryogenic temperature, understand the change of transconductance, currents, threshold voltage, and understand the freeze-out and impurity field ionization effect.

They will then study how to design a low noise amplifier (LNA), which is used in most qubit readout circuits at cryogenic temperature. The students already have substantial knowledge of LNA design and circuit layout from other EE classes. This class helps them understand the design trade-off at cryogenic temperatures. Moreover, the qubit readout circuit is used as an example to illustrate how microwave knowledge plays an important role in quantum computing (such as the generation of I-Q blobs).

TABLE II. SPRING TEACHING SCHEDULE OF CRYOGENIC NANOELECTRONICS (EE226)

Week	Class	Seminar
1	1	No Class
	2	Introduction/ Cryogenic Basics
2	3	Cryogenic Bulk MOSFET
	4	Cryogenic Bulk MOSFET
3	5	Cryogenic Bulk MOSFET
	6	Cryogenic SOI
4	7	Cryogenic SOI
	8	FinFET
5	9	Cryogenic FinFET
	10	Cryogenic FinFET/ Layout
6	11	HEMT
	12	Cryogenic HEMT
7	13	Quantum Effects
	14	Quantum Effects
8	15	Quantum Effects and Review
	16	Midterm
9	17	Noise Analysis
	18	Noise Analysis
10	19	Spring Recess
	20	Spring Recess
11	21	Noise Analysis
	22	Noise Analysis
12	23	Cryogenic Low Noise Amplifier
	24	Cryogenic Low Noise Amplifier
13	25	Cryogenic Low Noise Amplifier
	26	Cryogenic Low Noise Amplifier
14	27	Qubit Control/Sensing Device/Circuits
	28	Qubit Control/Sensing Device/Circuits
15	29	Qubit Control/Sensing Device/Circuits
	30	Qubit Control/Sensing Device/Circuits
16	31	Project Presentation
	32	Project Presentation
17	33	Review

For the project, the students will choose to either work on cryogenic device optimization using Technology-Computer-Aided Design (TCAD) or using spectre to design cryogenic LNA. TCAD is pretty well developed for 4.2K simulations [9]-[12]. Therefore, students are required to simulate their devices down to 4.2K. However, cryogenic models for circuit design are usually not available at 4.2K. So, they are only required to simulate down to 77K using available generic PDK at which the trends of the transconductance and output resistance are still reasonable.

IV. QUANTUM COMPUTING ARCHITECTURES (EE274)

In Quantum Computing Architectures (EE274), various qubit techniques will be introduced. This class will be first offered in Spring 2023. Fully understanding all possible quantum physical qubits requires many years of training in physics. In this class, many theories (e.g. second quantization) will be summarized as given. The students are requested to take them for granted or even memorize them as facts. Simulations will be emphasized so that the students can see the strong connection between quantum computing and traditional EE knowledge.

The use of non-quantum simulation tools is low-cost and a great advantage to be included in the QCI specialization, in particular, for EE students. For example, we will use HFSS to simulate the resonant cavity and Josephson Junction eigenmodes through classical EM simulations and then use methods such as Energy Participation Ratio, to help them understand the readout time and design of qubit. This is purely classical but the students can appreciate how close they are to quantum computing without expensive equipment and sophisticated math. Of course, EPR is very sophisticated math.

TABLE III: SPRING TEACHING SCHEDULE OF QUANTUM COMPUTING ARCHITECTURES (EE225)

Week	Class	Seminar
1	1	Review of Quantum Information Processing
	2	Review of Quantum Information Processing
2	3	Circuit Quantum Electrodynamics
	4	Circuit Quantum Electrodynamics
3	5	Circuit Quantum Electrodynamics
	6	Circuit Quantum Electrodynamics
4	7	Josephson Junction Qubit Basics
	8	Josephson Junction Qubit Basics
5	9	Josephson Junction Qubit Basics
	10	Josephson Junction Qubit Basics
6	11	Manipulation of JJ Qubit
	12	Manipulation of JJ Qubit
7	13	Readout of JJ Qubit
	14	Readout of JJ Qubit
8	15	Midterm
	16	Spin Qubit Physics
9	17	Spin Qubit Physics
	18	Spin Qubit Manipulation and Readout
10	19	Spring Recess
	20	Spring Recess
11	21	Spin Qubit Manipulation and Readout
	22	Spin Qubit Control Circuit Integration
12	23	Spin Qubit Control Circuit Integration
	24	Trapped Ion Qubits Physics
13	25	Trapped Ion Qubits Physics
	26	Trapped Ion Manipulation and Readout
14	27	Trapped Ion Manipulation and Readout
	28	Photonic Qubit Manipulation and Readout
15	29	Photonic Qubit Manipulation and Readout
	30	Photonic Qubit Manipulation and Readout
16	31	Photonic Qubit Manipulation and Readout
	32	Review

So we need to encapsulate it like using KCL, KVL to encapsulate Maxwell's equations in the analysis.

Therefore, another essential criterion for the success of QISE education is to develop methodologies (but rigorous) to hide quantum mechanics and math. But if a theory is already pretty complete, such as EPR, we can just teach them the skill without the derivation.

While this class has not been offered, we have experimented with this on the senior project [13] and we found that with the training in the earlier EM class, the students can pick up HFSS and apply to research successfully even though they do not have a very strong quantum mechanics background.

Table III shows the syllabus of EE274. Emphasis is on the manipulation and readout circuits which need contributions from engineers with EE background.

V. Discussion

For schools that do not have the resources to implement the specialization and to make all EE students quantum-aware, one may include QISE topics in all relevant classes after the first introductory quantum computing class, which can be created by following [4]. For example, the semiconductor class can include semiconductor qubit and Josephson Junction qubit; Circuit class can include cryogenic electronics and readout circuits; RF class can include EPR method; Digital Signal Processing class can include qubit readout signal processing; Machine learning class can include examples for accurate quantum gate control. All these are classical materials but they will train all EE students to be quantum-aware.

VI. Conclusions

In this paper, we discuss the Quantum Computing and Information Specialization of the EE Master Degree at San Jose State University, a Minority Serving Institution. Three classes are created for this purpose. They are created to minimize the investment and maximize the return for the EE students to be quantum-aware and to be ready to join the quantum technology industry.

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Thanks to the reviewers' feedback, it is also believed that the specialization can be improved by 1) including the applications of QISE in the industry, e.g. Quantum Optimization, VQE, QAOA, Quantum Communications, Quantum Machine Learning, etc., 2) emphasizing that not all quantum technologies need to be cryogenic, and 3) "Qiskit Metal" may be a better platform for EE274 [14].

References

[1] https://sanfrancisco.cbslocal.com/2015/08/25/san-jose-state-university-sjsu-silicon-valley-tech-jobs-apple-cisco-hewlett-packard/

[2] A. Asfaw et al., "Building a Quantum Engineering Undergraduate Program," in IEEE Transactions on Education, vol. 65, no. 2, pp. 220-242, May 2022, doi: 10.1109/TE.2022.3144943.

[3] Michael A. Nielsen, Isaac L. Chuang, Quantum Computation and Quantum Information, 2nd ed., Cambridge University Press, 2021.

[4] HY Wong, Introduction to Quantum Computing: From a Layperson to a Programmer in 30 Steps. Switzerland: Springer Nature, 2022, pp. 170. https://doi.org/10.1007/978-3-030-98339-0. ISBN-10: 3030983382.

[5] H. J. Morrell and H. Y. Wong, "Study of using Quantum Computer to Solve Poisson Equation in Gate Insulators," 2021 International Conference on Simulation of Semiconductor Processes and Devices (SISPAD), 2021, pp. 69-72, doi: 10.1109/SISPAD54002.2021.9592604.

[6] Hector Morrell, Anika Zaman, and Hiu Yung Wong, "Step-by-Step HHL Algorithm Walkthrough to Enhance the Understanding of Critical Quantum Computing Concepts," arXiv:2108.09004v3.

[7] Anika Zaman and Hiu Yung Wong, "Study of Error Propagation and Generation in Harrow-Hassidim-Lloyd (HHL) Quantum Algorithm," 2022 IEEE Latin America Electron Devices Conference (LAEDC), 2022.

[8] https://quantum-computing.ibm.com/

[9] Unified Undoped Bulk Silicon Electron and Hole Mobility Model," in IEEE Transactions on Electron Devices, doi: 10.1109/TED.2022.3152471. (2022)

[10] Prabjot Dhillon, Nguyen Cong Dao, Philip H. W. Leong, and Hiu Yung Wong, "TCAD Modeling of Cryogenic nMOSFET ON-State Current and Subthreshold Slope," 2021 International Conference on Simulation of Semiconductor Processes and Devices (SISPAD), 2021, pp. 255-258, doi: 10.1109/SISPAD54002.2021.9592586.

[11] Tom Jiao and Hiu Yung Wong, "Robust Cryogenic Ab-initio Quantum Transport Simulation for LG=10nm Nanowire," submitted to Solid-State Electronics, 2022.

[12] Hiu Yung Wong, "Calibrated Si Mobility and Incomplete Ionization Models with Field Dependent Ionization Energy for Cryogenic Simulations," IEEE 2020 International Conference on Simulation of Semiconductor Processes and Devices, pp193-196, doi: 10.23919/SISPAD49475.2020.9241599.

[13] Harsaroop Dhillon, Yaniv Jacob Rosen, Kristin Beck, and Hiu Yung Wong", Simulation of Single-shot Qubit Readout of a 2-Qubit Superconducting System with Noise Analysis," 2022 IEEE Latin America Electron Devices Conference (LAEDC), 2022.

[14] https://qiskit.org/metal/