MAS.S65: Piezoelectrics for Ultrasonic Biomedical Devices

Course instructor: Canan Dagdeviren

Supporting staff members: Lin Zhang, Md Osman Goni Nayeem

Style

Flexible; Individual projects (teamwork can also be possible upon the wish of students).

To pass, you must: (i) attend all the class lectures, (ii) participate during the experimental/simulation sessions, and (iii) submit the project(s) at the end of course. By the end of Class #1, students must decide whether to register or drop the course.

Overview

This is a special topic on piezoelectric materials and devices, which have become a leading source of functional and intelligent electronics in a vast array of applications, from personal healthcare to industrial equipment. The instructor anticipates that this unique course will shed light on the present state of research and development within the community of piezoelectric materials and ultrasound devices for biomedical applications. It begins with a comprehensive summary of the history of piezoelectrics and current hot research topics. Second, it covers all aspects of the materials starting from fundamental concepts, including the theory of piezoelectricity, and the physics of piezoelectric materials and their characteristics. Third, it demonstrates advanced electronic devices, including sensors, actuators, harvesters, and transducers. Fourth, it will cover cutting-edge applications of piezoelectric ultrasound for medical imaging, energy transfer, and neurostimulations. Last but not least, students will be trained on modelling ultrasonic propagation to design medical devices using different simulation software like COMSOL and PiezoCAD. In the meantime, students will obtain practical expertise in synthesizing and characterizing piezoelectric materials and manufacturing and measuring piezoelectric devices for engineering and biomedical applications. On the course website, course-related books/articles/notes/video tutorials are provided. The final projects are to submit digital drawings (2D/3D) and their corresponding simulation results of the proposed piezoelectric medical devices based on the interest of the students.

Objectives

1. To gain knowledge from experts in the piezoelectric and ultrasound research field,
2. To understand the impact of microfabricated devices on society,
3. To encourage participation in class by the asking of questions,
4. To experience the piezoelectric materials/devices fabrication and characterization,
5. To draw and simulate the performance of different piezoelectric ultrasound based medical devices.
6. To write a scientific report on the research findings and experiments as a team.

Schedule (Lecture sessions: ≥3 hrs/class; Experimental/Simulation sessions: ≥3 hrs/class)

Class	Session	Topics
Part A: Piezoelectric fundamentals & applications		
No. 1	**Class**	**Introduction** - Syllabus overview & what you can learn from this class - The smart materials & the role of piezoelectrics - Dielectrics/piezoelectrics/ferroelectrics subsets - Origin of piezoelectric phenomenon - Structure & piezoelectric equations - Parameters, full matrix, and governing equations - Piezoelectric constants and important piezoelectric parameters/factors - Resonant crystal geometries & modes of vibration - Fundamental & harmonic frequencies and corresponding modes of vibrations - Perovskite structure and importance of Curie temperature - Tetragonal, orthorhombic, rhombohedral, etc. phases - Importance of morphotropic & polymorphic phase boundary
No. 2	**Class**	**(A) Piezoelectric materials: crystal and ceramics** - Different types of ceramics: lead-based and lead-free types - Fabrication and preparation - Important crystal and ceramic properties e.g., longitudinal velocity, impedance, d_{33}, k_{33}, dielectric constant, loss, etc. - Performance and recent important work **(B) Piezoelectric materials: films (inorganic and organic)** - Different types of films - Fabrication and preparation - Important properties - Performance and recent important work **(C) Piezoelectric materials: composites** - 10 types of connection - Fabrication and preparation of composites - Important properties - Performance and recent important work
No. 3	**Class**	**(A) Piezoelectric devices: sensors** - device examples - performance - applications **(B) Piezoelectric devices: actuators** - device examples - performance - applications **(C) Piezoelectric devices: harvesters** - device examples

		- performance - applications
No. 4	**Experimental**	**Piezoelectric materials characterization** - Exhibit different piezoelectric materials: ceramics/crystal/thin film - Impedance analysis - LDV measurement - Parameters calculation
	Part B: Ultrasound fundamentals & applications	
No. 5	**Class**	**Introduction of ultrasound** - Physics - Propagation model: wave equations & interaction of Sound and Media - Importance of frequency/wavelength/velocity, impedance matching, & attenuation - How to generate ultrasound wave - Ultrasound transducers - Why arrays: 1D array, 1.5D array, 2D array - Types of arrays (linear, curvilinear, phased, annular, sector, theta-theta, PMUT array, etc.) and comparison, and selection criteria for end-use applications - Importance of understanding tissue attenuation coefficient and acoustic loss - Attenuation of a soft tissue as a function of frequency
No. 6	**Class**	**Ultrasound transducers** - The structure of ultrasound transducers - Performance parameters with examples based on different end uses - Important factors in US: intensity, amplitude, pulse duration, duty cycle - Importance of press focusing, focusing lens, matching, and backing layers - Equivalent circuit transducer model: KLM model - Demonstrating AUTOCAD application for microfabricated array and electrode trace designing
No. 7	**Class**	**Ultrasound applications: imaging** - Background of ultrasound imaging - Different modes of imaging: A, B, M, and Doppler mode - Performance parameters with examples based on different end uses - Examples of ultrasound imaging - Examples of different transducer array designs for imaging (comparing previous & recent works) - Importance of piezoelectric material selection for imaging (comparing previous & recent works)
No. 8	**Class**	**Ultrasound applications: imaging** - Beamforming & steering - Pulse-echo/Chirp - Axial & lateral dimensions of the beam - Delay and sum method for image generation - Signal processing - Circuit design and working principle - Ultrasound imaging analysis
No. 9	**Class**	**Ultrasound applications: wireless energy transfer & communication** - Physics

		- Applications - Parameters for ultrasound energy harvesting sensitivity - Importance of receiver/transmitter design selection - Transmitter & receiver parameters for energy transfer & communication - Examples of different ultrasonic receiver/transmitter designs for energy transfer (comparing previous & recent works) - Importance of piezoelectric materials selection for energy transfer (comparing previous & recent works)
No. 10	**Experimental**	- Fundamental of PiezoCAD for piezoelectric transducer - Discussion on simulation parameters for ultrasound transducer - Demonstrating PiezoCAD simulation experiments to investigate the effect of design parameters for different end-uses of: (i) ultrasonic transducer for medical imaging and (ii) ultrasonic transmitting transducer for energy transfer
No. 11	**Class**	**Ultrasound applications: Stimulation/therapy, drug delivery & tissue characterization with low and high frequency transducer** - Physics - Applications - Propagation model - Frequency selection like HIFU, LIFU, etc. - Different stimulation techniques: focused, pulsed, continuous, etc. - Neurostimulation, thermal ablation, lithotripsy, elastography, therapeutic contrast agent - Tissue characterization: radiology, cardiac application, etc. - Drug delivery: methodology and current state of the earth - Examples of different ultrasonic device designs for stimulation/therapy, drug delivery, and tissue characterization
No. 12	**Class & Experimental**	**(A) Piezoelectric Micromachined Ultrasound Transducer (PMUT)** - Physics - Applications - Propagation model - Frequency and materials selection & others **(B) AUTOCAD application for designing microfabricated PMUTs** **(C) Demonstrating COMSOL/On-Scale simulation experiments for profiling the piezoelectric ultrasound stimulation and investigate the effect of design parameters**
No. 13	**Project realization #1**	**Medical imaging transducer design: Draw 2D/3D image of your piezoelectric transducer & apply simulation using PiezoCAD for its performance characterization**
No 14	**Project realization #2**	**Wireless energy harvester design: Draw 2D/3D image of your piezoelectric harvester & apply simulation using PiezoCAD for its performance characterization**

Class calendar:

September 2022

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
				1	2	3
4	5 Holiday- Labor Day	6	7	8 Class no 1	9	10
11	12	13	14	15 Class no 2	16	17
18	19	20	21	22 Class no 3	23	24
25	26	27	28	29 Class no 4	30	

October 2022

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
						1
2	3	4	5	6 Class no 5	7	8
9	10 Holiday- Indigenous Peoples' Day	11	12	13 Class no 6	14	15
16	17	18	19	20 Class no 7	21	22
23	24	25	26	27 Class no 8	28	29
30	31					

conformable decoders

November 2022

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
		1	2	3 Class no 9	4	5
6	7	8	9	10 Class no 10	11 Holiday- Veterans' Day	12
13	14	15	16	17 Class no 11	18	19
20	21	22	23	24 Holiday- Thanksgiving Day	25 Holiday- Day After Thanksgiving	26
27	28	29	30			

December 2022

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
				1 Class no 12	2	3
4	5	6	7	8 Class no 13	9	10
11	12	13	14	15 Class no 14	16	17
18	19	20	21	22 Class 15	23	24
25 Holiday- Christmas Day	26	27	28	29	30	31