Optical filter design, fabrication and characterization; A multifaceted approach to project based curriculum

Dr. Scott Ryan Kirkpatrick, Rose-Hulman Institute of Technology

Scott Kirkpatrick is an Assistant Professor of Physics and Optical Engineering at Rose-Hulman Institute of Technology. He teaches physics, semiconductor processes, and micro electrical and mechanical systems (MEMS). His research interests include heat engines, magnetron sputtering, and nanomaterial self-assembly. His masters thesis work at the University of Nebraska Lincoln focused on reactive sputtering process control. His doctoral dissertation at the University of Nebraska Lincoln investigated High Power Impulse Magnetron Sputtering.

Dr. Maarij M Syed, Rose-Hulman Institute of Tech

Dr. Maarij Syed has been actively involved in the area of magneto-optics. His background is in the magneto-optics of quantum heterostructures and magnetic bulk materials. During his time here at Rose-Hulman he has focused on building a magneto-optics lab and developing various magneto-optics experiments for research and for student projects and classes. Dr. Syed has also used other reflection based techniques (e.g. ellipsometry) in his work, especially in the area of polymer film characterization. On the pedagogical side, Dr. Syed has been involved in evaluating the studio style format for physics courses. He has been teaching the introductory sequence in this format where students learn through hands-on activities. He has also served as a judge for the Indiana State Science and Engineering Fair for the last eight years.

Dr. Richard W. Liptak, Rose-Hulman Institute of Technology

Metal-Dielectric-Metal (MDM) Filters: Project Based Learning for EP Curriculum

Maarij Syed, Scott Kirkpatrick, and Richard Liptak

Department of Physics & Optical Engineering Rose-Hulman Institute of Technology
5500 Wabash Ave, Terre Haute, Indiana, 47803

1. Abstract

Engineering Physics (EP), at its core, is a multidisciplinary approach to solving problems that require insights from various traditional disciplines. The EP curriculum at Rose-Hulman Institute of Technology strives to foster this multidisciplinary approach by incorporating student projects that require integrating concepts and principles from various fields into a meaningful approach toward a realistic solution. These projects, ideally involve a design / problem statement, a fabrication step, and a testing or characterization stage. As an example of such an approach, a new lab is proposed to provide students with an understanding of optics, thin film depositions and real world constraints. Students are presented with the concept of a Fabry-Perot (FP) filter, and are asked to create a metal-dielectric-metal multilayer film to produce filters in the visible spectrum. The filters are then analyzed with reflectance spectroscopy and ellipsometry. The results are then analyzed for consistency, and to gain insights into the details of the fabrication process and resulting structure.

2. Introduction

The project involves fabricating and analyzing a metal-dielectric-metal (MDM) film. MDM is a thin layer of a highly reflective metal (Cr), then a layer of highly transparent dielectric material (SiO_2), and finally a thin layer of a highly reflective metal. The entire structure is built on a Si wafer. When light enters an MDM film, it can reflect off of the first layer of metal, or it can pass through the metal and dielectric, and reflect off of the second layer of metal. When white light enters an MDM film, it acts much like a FP etalon [1]; the light interferes constructively and the reflectance of the film peaks at a certain wavelength. The peak reflectance wavelength, like a Fabry-Perot etalon, is dependent on the optical path

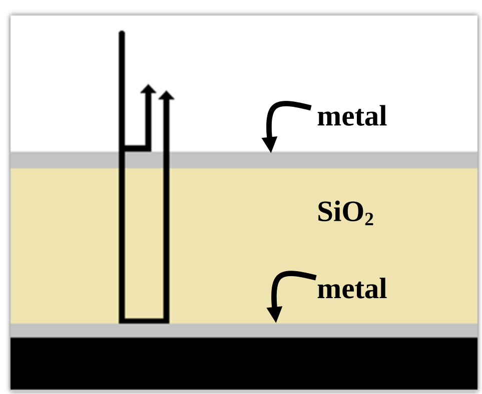

Fig. 1 A single MDM "layer" and a 1st order optical interference

length, i.e., the thickness of the dielectric material, the index of refraction, and the angle of incidence. By carefully controlling the thickness of the dielectric material, one can change the reflectance peak of the film. This process can be visible to the naked eye, depending on the thickness of the film [2]. A color change in the film is indicative of change in the reflectance peak. By adding more layers, the width of the reflectance peak can be decreased. Also, as more layers are added, the peak reflectance increases. The fabricated structures are also analyzed by reflectance and spectroscopic ellipsometry to understand how the actual sample differs from the ideal structure that is proposed. We also discuss how this project can be incorporated into different classes with varying emphasis.

2.1 Project Flow

While the lab project can be implemented at varying levels of detail and emphasis can be placed on various aspects of the project, it is worth noting that students are always required to respond to a real world design problem. We visualize the project as consisting of three stages.

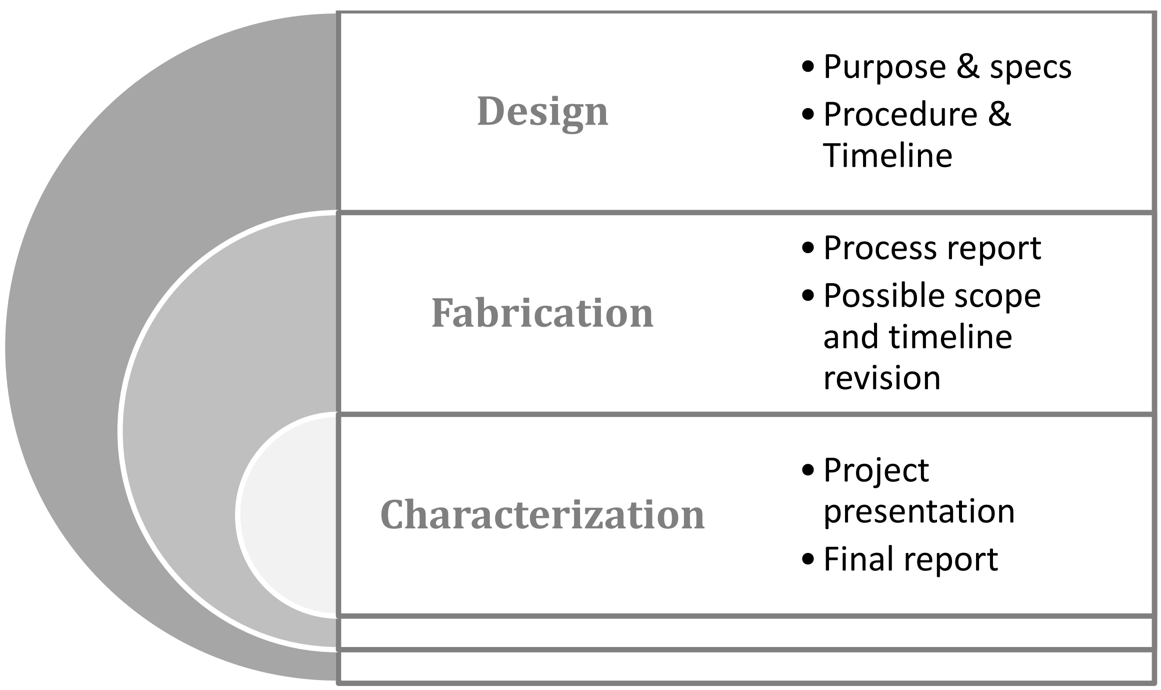

Fig. 2 Basic components of the proposed MDM filter lab

Each stage, as outlined above, consists of a progress report and the project concludes with a final presentation where the team presents and defends its product and process implementation. The design statement may vary in terms of its overall scope (see below) but it is always required to state the center wavelength and the bandwidth of the reflectance filter. It is expected that students will be able to defend these parameters by presenting relevant system modeling and calculations. It is also expected that students will keep track of their group meetings and will make available minutes from these meetings in the progress reports that are filed with the instructor at the end of the design and fabrication stages. During and after the fabrication stage, the team may be required to include in their report how progress thus far compares to the initial proposed timeline, and if needed (and if possible) should the timeline be modified. During the final presentation students are expected to not only describe what they accomplished but also draw quantitative comparisons (in terms of performance and cost) with commercially available reflectance filters. Final project presentation is also expected to be accompanied by a self-reflection statement from all the team members that would describe their learning experience.

The two main modes of implementation that are visualized for this project are: as design project for the design sequence (EP415 – EP417) and for the Advanced MEMS course (EP411). We discuss the particulars of these two modalities below

2.2 Implementation Modalities

The two modalities (Design Sequence or Advanced MEMS) differ in terms of time and resources that are available to the students. Both courses are typically taken by the students in their senior year. Design sequence allows for three person teams and the project allows for a more elaborate implementation. Given that teams have two quarters to complete the project, the version of the design sequence they carry out is far more detailed. The team that adopts this project is required to first carry out an initial stage (*design optimization stage*; still involving design, fabrication, and characterization) where they prove that they can produce an MDM filter that is composed of a single iteration of the MDM structure. The "final report" for this stage pertains to only this stage and will not contain a self-reflection statement. It is however expected to contain a discussion and proposal of alternative design process and parameters. These alternatives, that may prove more efficient and or lead to better filters, are to be discussed with reference to some figure(s) of merit (FOM) that the students arrive at while characterizing the initial MDM filter. Obvious choices for device FOM would be percent reflectance and bandwidth of the MDM filter. Other FOMs could be developed around cost and performance of the final device. Guided by these choices and outcomes from the initial stage, students carry out a second iteration (*process improvement cycle*) of the process outlined in Fig. 2. To help students carry out this process in a more structured manner they will be required to provide the number of iterations of the MDM structure in the design statement for the second stage. This proposed structure is again expected to be backed up by relevant modeling and calculations.

The implementation scheme in Advanced MEMS is modified due to two considerations. First of all, the students will only have one term to complete the project. Moreover, they will work individually or at most in groups of two. They may not have the resources of the larger group and so it is expected that students who take on this project will be comfortable with the necessary background that is described in section 2.3. The project will flow along the same lines except that there will only be one stage and the emphasis will be more tilted towards the growth process, given that these students will have completed the prerequisite course, Intro to MEMS (EP410). In one possible version, students may compare and contrast single iteration MDM structures with two different metal layers (Cr vs. Al) and explore the relative advantages of using one metal vs. the other in terms of growth process considerations like time, ease of implementation, cost estimate of the overall structure, etc.

2.3 Facilities Required

The project, as envisioned at our institution, requires a clean room facility equipped with deposition capability (magnetron sputtering, e-beam deposition, etc.), and typical characterization facilities. Ultimately the level of detailed characterization is limited by what is available. In our case, characterization has been based on reflectance (Filmetrics™, F20) and multi-angle, multi-wavelength ellipsometric analysis (J. A. Woollam™, Alpha-SE). Additional characterization techniques like X-ray Diffraction and Atomic Force Microscopy can also be implemented in a more detailed version of the project. For our more independent students these and other options are always there as part of the overall scheme of characterization, should they choose to use them.

2.4 Core Concepts & Learning Outcomes

In terms of core concepts the project starts with a design statement that requires a basic background in the theory of optical filters and familiarity with Fresnel equations. These topics are either learned by students in courses they take as electives or in core courses if they are double majoring in Optical Engineering (OE). In one possible version, students work in teams of three, and not every member is necessarily conversant with the details of optical filter design at the start of the project (but at least one team member is proficient in the area).

The next area of core concepts is device growth and fabrication. Students typically have been exposed to the relevant information in as many as three lead up courses. Two of these form the basic device sequence of the EP curriculum and are listed as PH405 (Introduction to semiconductor devices I) and EP406 (Semiconductor Device and Fabrication II). Students are expected to finish these courses in their junior year. In addition, nearly all of the students have also taken Introduction to MEMS (EP410), a course in which students are required to work in teams in a clean room environment and fabricate and characterize various MEMS devices (typically heat actuators).

Characterization stage requires students to put their knowledge of Fresnel equations and reflectance to work. It is advisable to make the students think of the optical characterization steps as building on one another. First a Reflectance measurement is carried out to confirm the basic outcome, which if the project has been executed properly, should also be obvious visually. Reflectance measurements are carried out at normal incidence and can give the basic information about the device parameters discussed earlier in section 2.1; namely, center wavelength and width of the reflection peak. Model building, if any, at this stage is fairly rudimentary. Layers for the MDM stack can be modeled by the student or the software program based on deposition run time and input provided by the quartz crystal monitor (or any other sensor that monitors film growth). The ellipsometric analysis that follows is to be far more in-depth. Ellipsometry allows for using polarized light. This allows for more detailed models where students can explore issues like layer non-uniformity, presence of interface layers, etc. Students also learn the vital lesson that a useful characterization scheme involves measurements that give complimentary information and this process in turn helps elucidate the overall features and response of a real-world device.

In addition to the core concepts that are utilized, if this project is implemented in the lab sequence EP415 – 417, students are also expected to learn project management skills like time management, team building, delegation of tasks, management of resources, benchmarking, and comparative analysis of existing products. Similarly, if it is run as an EP411 project the aforementioned skills will help the students in carrying out the projects they encounter in EP 415 – 417.

2.5 Current Implementation

At Rose-Hulman, our implementation of this idea so far has followed a customary route. Instead of attempting a full-scale implementation, various pieces of this project have been tried out as independent research projects and at this stage we feel that the project can be implemented successfully. James Folberth and Kellen Stolze (EP, 2012) worked on fabrication and reflectance measurements. They built five multilayer and various single layer MDM stacks designed to act as reflectance filters for different wavelengths. Number of iterations of the MDM stack was also varied to see the effect of multiple layers on the reflectance peak. Chris Gewirtz (EP, 2014) has been working on ellipsometric models for the filter samples.

2.6 Initial Results

Filters of varying layer thickness were fabricated. At this stage metal layer composition and thickness was held fixed (Cr and 5.0 nm). The dielectric layer was of varying thickness (to have different peak wavelength) but was always SiO_2 (dry oxidation method). Some of these filters are shown in Fig. 3. Visual inspection confirms that different filters correspond to different peak wavelengths.

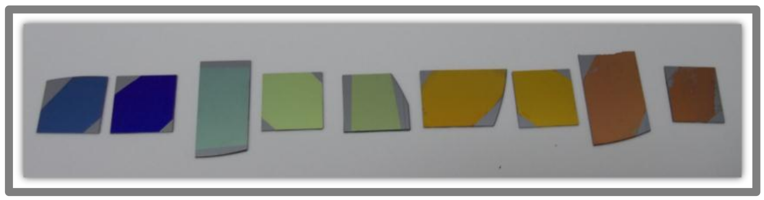

Fig. 3 Different MDM filters corresponding to different colors

Reflectance spectra were also collected and allowed the students to see the difference between the reflectance profiles of a single layer MDM structure vs. MDM filters made with multiple layers. Ellipsometric analysis has revealed much more information regarding the non-idealities present in the MDM structures (e.g., surface roughness, interfaces, etc.). We plan to publish a technical report based on these results in the near future.

3. Conclusions

In conclusion, we have presented a proposal for a hands-on lab project that incorporates many of the key characteristics that are viewed as desirable in an EP curriculum. The project relies on interdisciplinary teams that have to work together in a timely manner to design and deliver a product that can be benchmarked against real-world counterparts. In doing so students will not only be exposed to the entire design, improvement, and validation cycle, they would also be made aware of the very real time and resource constraints that any design professional faces in carrying out such processes in a real-world setting.

References

1. G. Fowles, “Introduction to Modern Optics”, 2^{nd} Ed. Dover Publishing, NY, p. 90-96.
2. Kruschwitz, Jennifer, *SiO2 (Silicon Dioxide)*, www.kruschwitz.com (2011).