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Schaeffler iCVD Coating Machine

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SENIOR DESIGN

MECE 471

HONORS PROJECT

MECE 497

By

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Abstract

Chemical Vapor Deposition (CVD) is mutual technology used to deposit thin film through a gaseous phase by vaporizing the solid materials. This conventional process usually requires high thermal stability of the materials, which is not applicable for most of the polymeric materials. Therefore, a novel process, initiated Chemical Vapor Deposition (iCVD) is developed by introducing the gaseous monument and initiator to form the thin film *in-situ*. By adjusting the free-radical polymerization in the vapor phase, a variety of thin and uniform polymer films can be achieved. Depending on the chemistry, iCVD has many categories. This report explains the design and assembly process of an iCVD machine to meet the company's applications for polymer thin film deposition. The mass flow controlling, thermal management and vacuum monitoring system have been successfully designed and built. This enables the precise control the gaseous reactant feeding and film deposition rate. Meanwhile, the machine is mobile and modular, allowing for easy movement in the lab environment and future upgrades. The device will be used to characterize polymer coatings for use in coating metallic anode battery components to counteract harmful side reactions, thus increasing the feasibility of large-scale metallic anode solid-state battery production.

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1. Introduction

This report details the research, requirements, design, building, and application of an iCVD machine for battery research. The purpose of the machine is to deposit thin polymer coatings onto substrates such as silicon wafers and later battery components such as lithium metal and solid electrolyte powder.

1.1 Requirements

Requirements were decided collaboratively between Schaeffler and the designer to determine how the device will best serve research in the future. These requirements were used as a guideline for the design but were flexible. The first of these requirements was that the energy source should be adjustable. The logic behind this concept is that eventually the tube furnace could be removed, and a UV light source take its place. This would allow the use of a monomer that could be polymerized via UV light as opposed to or in conjunction with heat. The next requirement is that the machine must be mobile. Mobility is important for the machine so that it can be easily moved around the lab as it grows and rearranges. Modularity is also important for the reactor because this device is going to be used for research and development, therefore the machine should be able to be modified easily. Another requirement is that the flow rates must be adjustable. The flow rate of the system is very important as it can control the thickness of the coating. The final requirement is that the system must be able to accommodate various process gases so that different coatings can be experimented with in the future.

2. Design

The design of this machine was based on requirements decided jointly by Schaeffler and the designer. The design is one of an entire system, built up of multiple elements. First, background information was considered in order to perform research relevant to the topic of chemical vapor deposition. After the topic was understood, brainstorming was done to decide the best layout for the given space and planned working activities. Next, this basic sketch was used to select the components and design the adapters necessary to assemble the machine. The details of this process, and the components therein, are detailed in this section of the report.

2.1 Background

The background of this project lies in Schaeffler's interest in furthering the research effort of all solid-state batteries so they can be brought to market. To understand this struggle, the typical lithium-ion battery chemistry must be understood. The batteries used in typical phones, laptops, and EVs today are liquid electrolyte lithium-ion batteries that have three main components; a cathode, anode, and polymer separator, all of which are saturated with a liquid electrolyte solution. This battery concept has been thoroughly researched and optimized over the years and is limited by its inherent material properties which make the cells unable to withstand high temperatures. This limitation is why liquid electrolyte batteries are a fire risk, have limited energy density, and cannot be fast charged without battery degradation. Although it is not the focus of Schaeffler's research, implementation of iCVD coating to increase the thermal stability of the liquid electrolyte separator has been proven by Yoo et al., 2015 [1].

All solid-state batteries solve the issues listed above by replacing the liquid electrolyte in the cell with a hard, compressed powder electrolyte, hence "solid-state". These solid-state batteries, or ASSBs, can withstand much higher temperatures than the liquid cells, as well as having the potential for higher energy density. Typical ASSBs have a cathode with active material such as LFP or NMC and a graphite anode, however lithium metal or metallic anodes have shown more promising energy density. The issue that is faced with metallic anodes is that the lithium metal is highly reactive, leading to unfavorable side reactions and uneven plating. This uneven plating leads to lithium dendrite growth which are sharp peaks of lithium metal that puncture the solid electrolyte layer, contacting the cathode and shorting out the battery, causing safety concerns.

A possible solution to these issues is very mechanical in nature, the application of a thin coating to the battery components. The challenge in creating such a coating is that it must be thin and permeable enough to allow the electron transfer vital to battery function, while being effective in its purpose to deter the side reactions that occur in a metallic anode cell. One of the methods that could be used to create this film is initiated chemical vapor deposition, or iCVD. The iCVD process involves combining a base monomer and initiator along with a carrier gas in a vacuum environment, then using some energy source to begin the polymerization process [2]. The polymer is delivered onto the substrate to form a conformal coating [3] that can evenly be distributed around complex geometries. The energy source typically used is heat and the coating thickness is controlled by the flowrate and time of the cycle. The iCVD process is also gentle enough to coat delicate materials such as battery components or even tissues [4] without damaging them.

This process is very customizable, and changes based on the user's requirements. There are some good examples of working iCVD reactors that have been documented by sources such as Dr. Karen Gleason's lab at MIT as well as various other research groups. At the University of Akron, there is currently an iCVD reactor that was tested and used as a reference for this project. The idea that these polymers can be uniformly coated in battery architecture has been proven [5].

2.2 Conceptual Design

Given the requirements for the project and what the purpose of the machine was, conceptual sketches were made first by hand then modeled in CAD. The basic design was modeled as seen in Fig. 1, and through a few iterations, the components were rearranged in a more efficient design as shown in Fig. 2. This model was scaled realistically to size to ensure it would fit in the lab space provided.

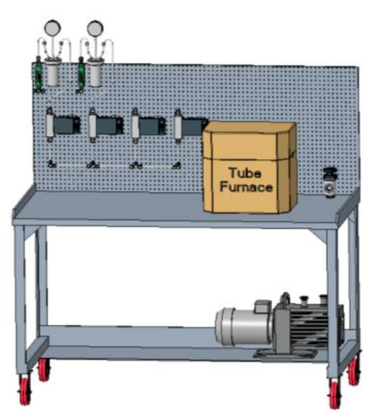

Figure 1: First iteration of conceptual model

Figure 2: Final iteration of conceptual model

2.3 Components

2.3.1 Cart

The mobile cart was chosen as the foundation for the machine because of reasons such as cost, mobility, and durability. Coming in at a price point of about $800, this cart made by Little Giant is a five-foot wide by two-foot-deep workbench with a lower shelf and an upper “pegboard” rigidly fixed to the back as seen in Fig. 3. This pegboard area allowed for the mounting of mass flow controllers and gas lines so that they were safe and out of the way of the work area. Building and manufacturing the cart was considered, but the resources necessary to fabricate, then powder coat the cart were much greater than simply purchasing the cart.

Figure 3: Cart used as the base of the machine

2.3.2 Gas Source

The gas source selected to start off the testing is lab grade argon in a gas cannister; this is the same argon used in the glovebox inert environments for solid-state battery research. This ensures that the process gas is of high quality and will facilitate a clean reaction on the surface of the substrate. In the future, it may be decided to use flammable gases to create other coatings, gases such as hydrogen or acetylene for example. This has been incorporated into the design, allowing an extra slot for another gas canister, see Fig. 4, along with a regulator from Harris Gas that is designed for these gases.

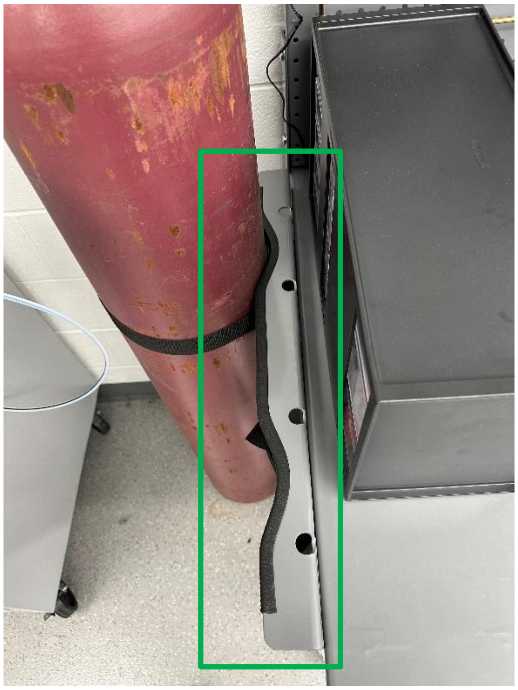

Figure 4: Tank mounting location

2.3.3 Mass Flow Controllers

Controlling the flow rate of the argon gas is paramount to the effectiveness of the coating process. It was decided that having multiple mass flow controllers with different flow rate capabilities would be the best way to ensure that there were multiple options to control the flow rate moving forward. Three controllers were selected, ranging from flow rates of 50 SCCM, 100 SCCM, and 2000 SCCM. These mass flow controllers have digital screens built in that allow the operator to control the flow rates without needing a secondary control module as seen in Fig. 5. This on-the-fly adjustment will be useful during the tuning phases when optimal flow rate is still something that is unknown.

Figure 5: Mass flow controller

2.3.4 Bubblers

The bubblers used for the machine were purchased from MTI and are made entirely of stainless steel as pictured in Fig. 6. The bubblers used in some of the iCVD machines found in the researching phase were made of glass, but this can be an issue because it allows some monomers to begin to polymerize in the bubbler due to UV initiation. The stainless bubblers also have shutoff valves on the inlet and outlet to close them off from the rest of the system whenever it is necessary.

Another advantage of stainless-steel bubblers over glass bubblers is that they can be wrapped with a heating sleeve like the one depicted in Fig. 7. Preheating the monomer and initiator before it gets to the final heating zone of the tube furnace may allow the reaction in the tube furnace to occur more readily as the delta between the two zones will be different. Another way to increase this delta is to implement backside cooling where the substrate lies [6].

Figure 6: Stainless-steel bubblers

Figure 7: Optional bubbler heating sleeve

2.3.5 Valves and Fittings

The valves used for this system were purchased from McMaster-Carr and are high precision ball valves made of 316 stainless-steel. The handle indicates flow direction, as shown in Fig. 8, and the fittings on the ends are ¼’’ compression fittings. These compression fittings are used throughout the system in conjunction with ¼’’ stainless tubing that was cut to size and compressed to form a good seal.

Figure 8: Panel mount on/off style valve

2.3.6 Tube Furnace

As mentioned earlier in the report, for the polymerization process to happen, an energy source is needed. This energy source can be plasma, UV, or heat, and for this reactor the energy source is heat via a tube furnace. The furnace used is a Thermo Scientific furnace capable of 1100℃, seen in Fig. 9, programmable with a digital keypad. The tube that substrate rests in and the gas flows through is a one-inch OD quartz tube. A silicate glass tube would not be ideal because of possible side reactions.

Figure 9: Thermo Scientific Tube Furnace

2.3.7 Tube Heat Source

Another way to preheat the monomer and initiator gas mixture before it gets to the tube furnace is to heat up the process lines. The process lines are ¼’’ stainless tubing that can be heated with heating cords such as the BriskHeat ones seen in Fig. 10 below. These cords have been purchased and are controlled with a Tempco self-powered thermal controller.

Figure 10: BriskHeat Heating Cord

2.3.8 Vacuum Pump

The vacuum pump selected for this system is one that was sourced from Schaeffler as it is the same model used to modulate pressure in the glove boxes. This pump is an Edwards RV12 Rotary Vane Vacuum Pump, picture in Fig. 11, with a peak pumping speed of 8.4 cfm and an ultimate pressure of $1.5*10^{-3}$ torr [7]. This pump is more than capable of providing the vacuum necessary and it may be replaced with a smaller pump later.

Figure 11: Edwards RV12 Vacuum Pump on cart

2.3.9 Exhaust System

After the gas travels through the tube furnace and over the substrate, it needs to safely exit the system. The quartz tube is connected to a series of one inch OD stainless-steel pipes that are then connected to a gate valve, picture in Fig. 12, that connects to the vacuum pump, a pressure gauge, and finally a flexible PTFE tube that can be routed to a safe exhaust location. The schematic of this system can be seen below in Fig. 13.

Figure 12: Gate valve

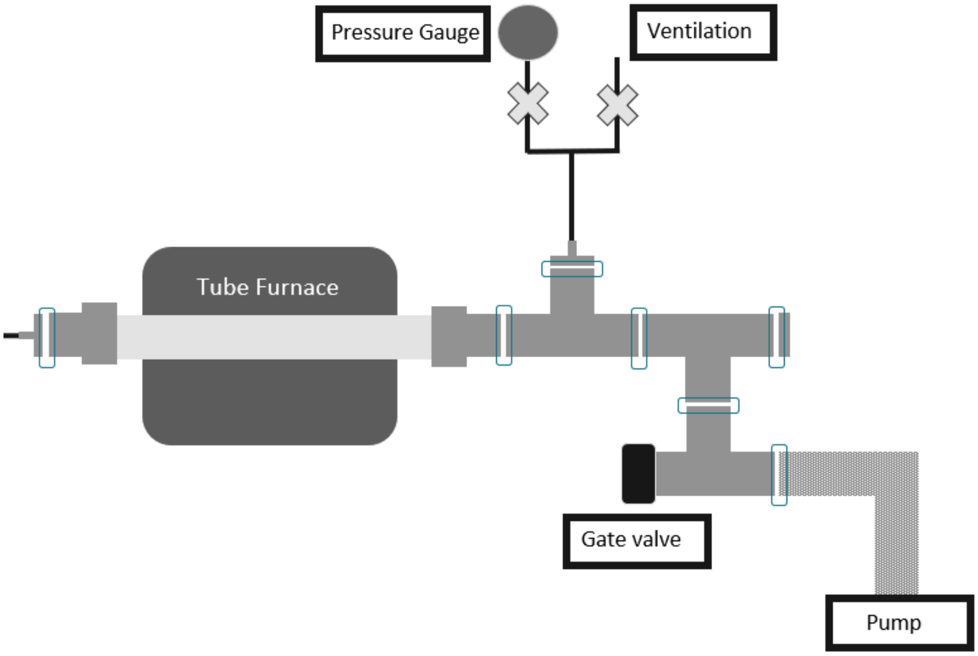

Figure 13: Exhaust side schematic

2.2.10 Adapters

The components listed above needed to be connected in an organized fashion, therefore custom adapters were fabricated. The mass flow controllers for example, had 10-32 tapped holes in the bottom that were not compatible to the one-inch grid hole pattern of the pegboard. This problem was solved by cutting up some aluminum and machining it to match the pattern of the holes. The larger holes at the top and bottom of the plate shown in Fig. 12 are adapted to the pegboard grid, while the smaller, diagonal holes are where the MFC bolts in.

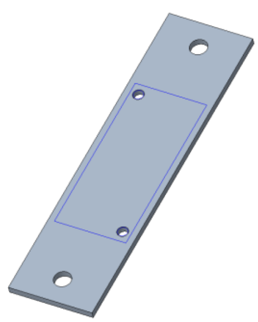

Figure 14: MFC adapter plate

Another part of the design that required an adapter was to adapt the scissor stand with the flat plate to the rounded, one inch diameter fitting that attaches to the quartz tube. The shape needed to complete this task was very odd, but it did not need to be very strong as it was realistically just a spacer block in compression. The part was first modeled using CAD based on hand measurements, then it was sliced, and 3D printed in house. Fig. 13 below shows the PLA-CF part in its place in the system.

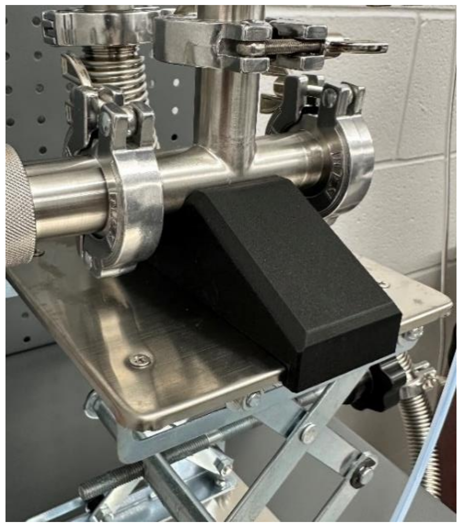

Figure 15: Scissor stand to tube adapter

3. Scope

This section of the report outlines how the reactor is to be used and what the plans for the project are moving forward. In Fig. 16 the system is shown in its entirety, combining the components from the previous section into one assembly. These components make up the four major components of the iCVD system: vapor delivery, pressure control, temperature control, and exhaust management [8].

Figure 16: Schaeffler iCVD reactor

3.1 Operation

The following testing operation sequence has been laid out to show how an operator would use the initiated chemical vapor deposition machine. The first step of the process is to remove the cap on the end of the tube so that the substrate can be loaded. This cap is highlighted in Fig. 17.

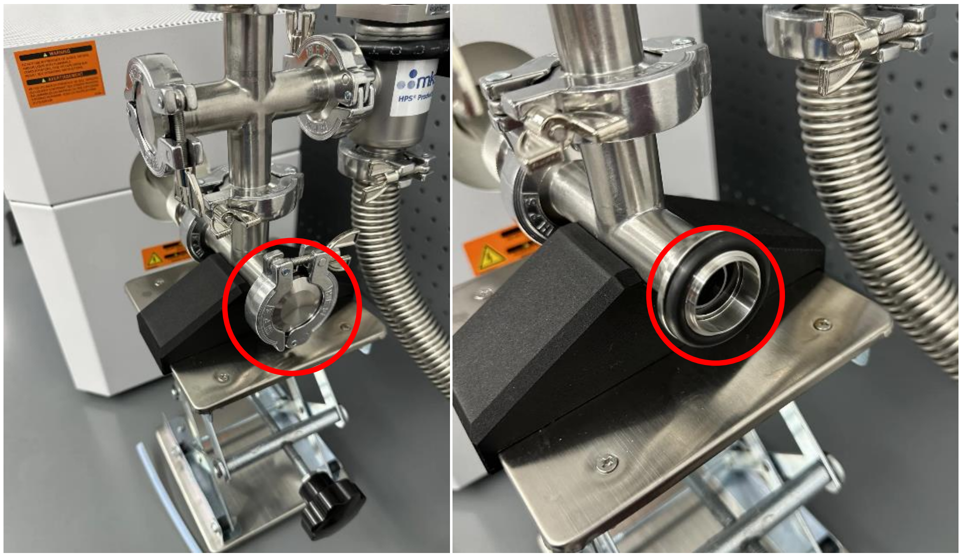

Figure 17: Removing end cap

Next a clean, silicon wafer, represented by green tape in Fig. 18, must be placed into a half inch quartz tube, so that this tube can be inserted into the one inch main tube.

Figure 18: Half inch quartz tube with sample loaded

This quartz tube will then be slid into the one-inch tube, with a magnet behind it. This magnet will be used to pull the sample tube into the heated section of the system, shown in Fig. 19, once the cap is placed back and the system is sealed.

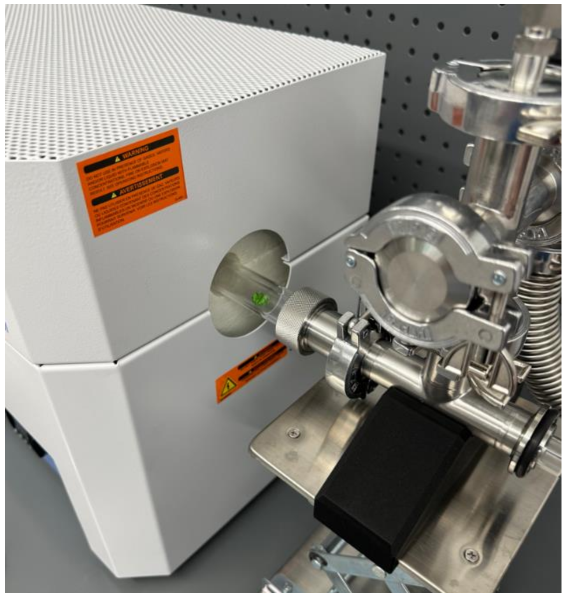

Figure 19: Sample is loaded into system

The next step is to set the tube furnace to the desired temperature for the reaction. This is done directly on the digital keypad of the furnace as highlighted in Fig. 20.

Figure 20: Tube furnace with temperature controller

The next step is to vacate the system of air so that later pure argon gas can be flowed through the system. This step involves first checking all the one-inch tube gaskets, along with the push to connect fasteners that hold the PTFE tubes in place. These areas are circled in Fig. 21.

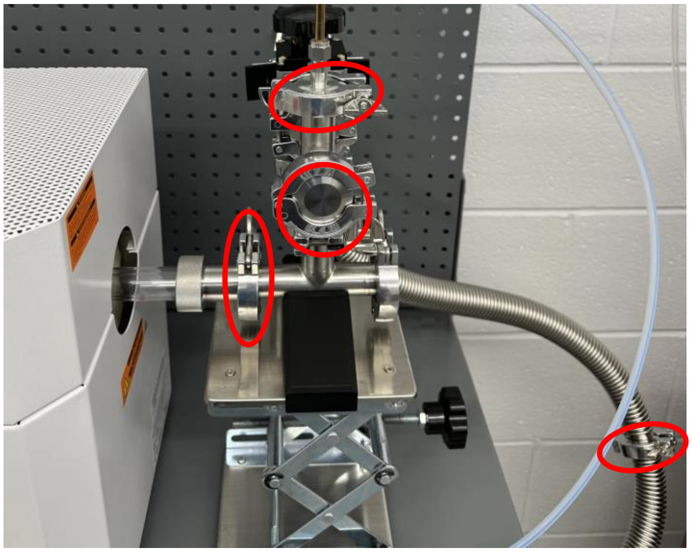

Figure 21: Exhaust side of reactor

Next, the correct valves must be opened to pull a vacuum on the entire system to remove the air. For a test using the 2000 SCCM mass flow controller the figure below shows, referring to Fig. 22, open the valves in green, and close the ones in red.

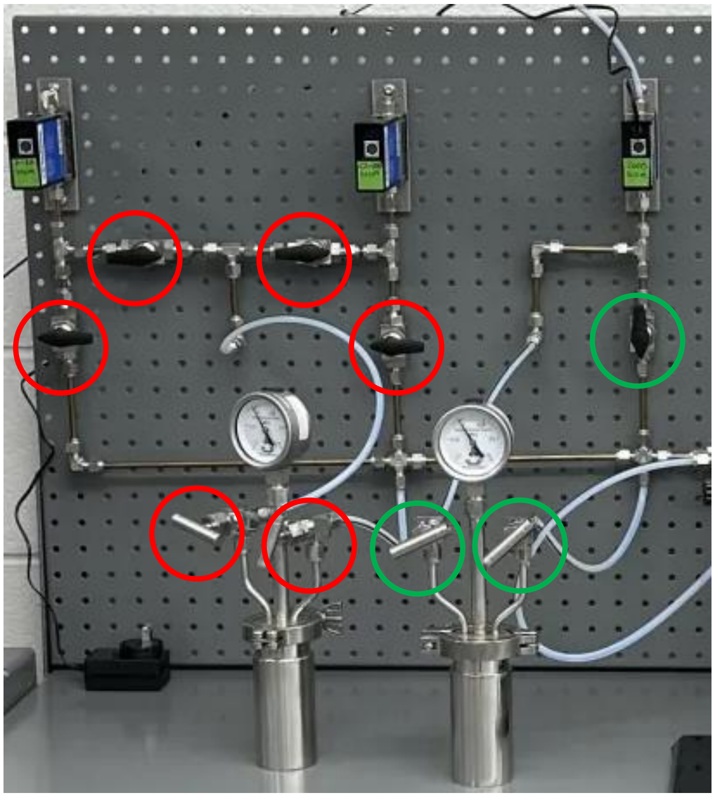

Figure 22: Valve orientation identified for pulling vacuum

Finally, the vacuum pump can be switched on and the vacuum gauge (Fig. 23) can be used to indicate the vacuum on the system. Adjust the vacuum with the gate valve (Fig. 24).

Figure 23: Vacuum gauge

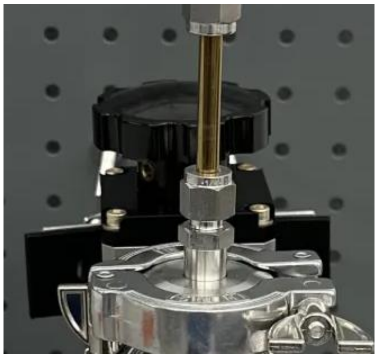

Figure 24: Gate valve

As the system is under vacuum the argon should be turned on using the regulator shown in Fig. 25, which can be adjusted to hold a certain pressure.

Figure 25: Argon tank with regulator

The vacuum pump should then be turned off and the argon should flow freely through the system as shown in Fig. 26 below. Ensure that the bubbler valves are turned off and excluded from this loop as seen in the figure.

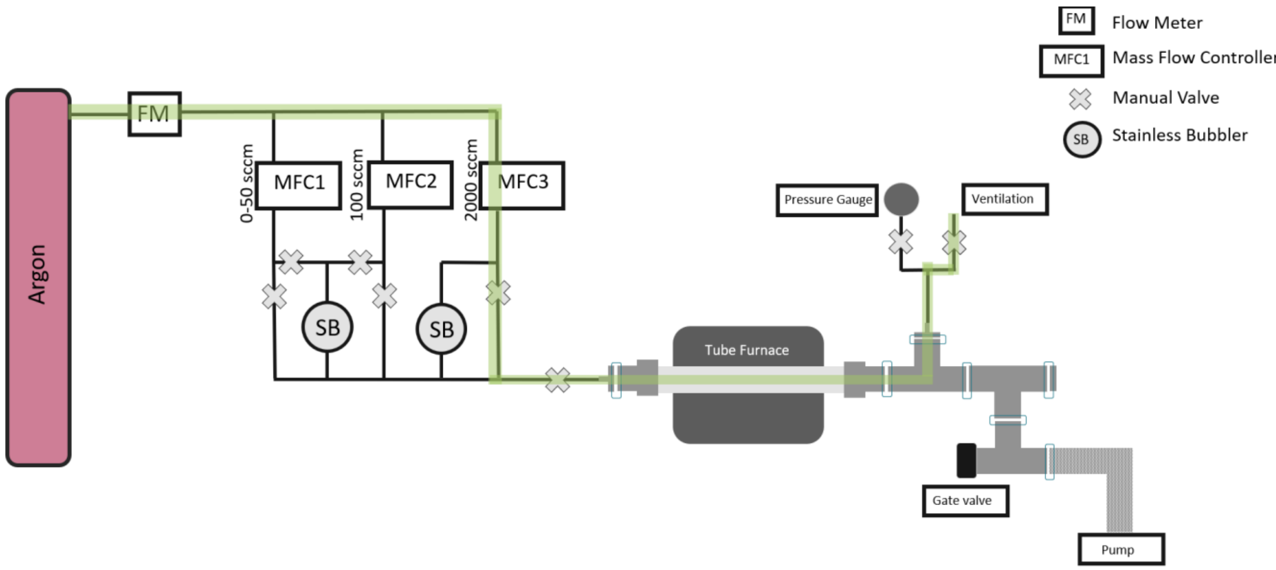

Figure 26: Cleaning cycle schematic

The next step is to add the monomer and initiator to the bubbler. First open the bubbler, ensuring to keep the valves closed so it is isolated from the argon flow loop. Insert the desired amount of monomer and initiator into the bubbler at the circled point in Fig. 27.

Figure 27: Stainless-steel bubbler with opening highlighted

Finally, the bubbler can be opened to be part of the system loop, and the polymerization can occur. The figure below shows the flow path highlighted in green. This path can be modified from the loop in Fig. 28 to go through the other mass flow controllers if a different flow rate is desired.

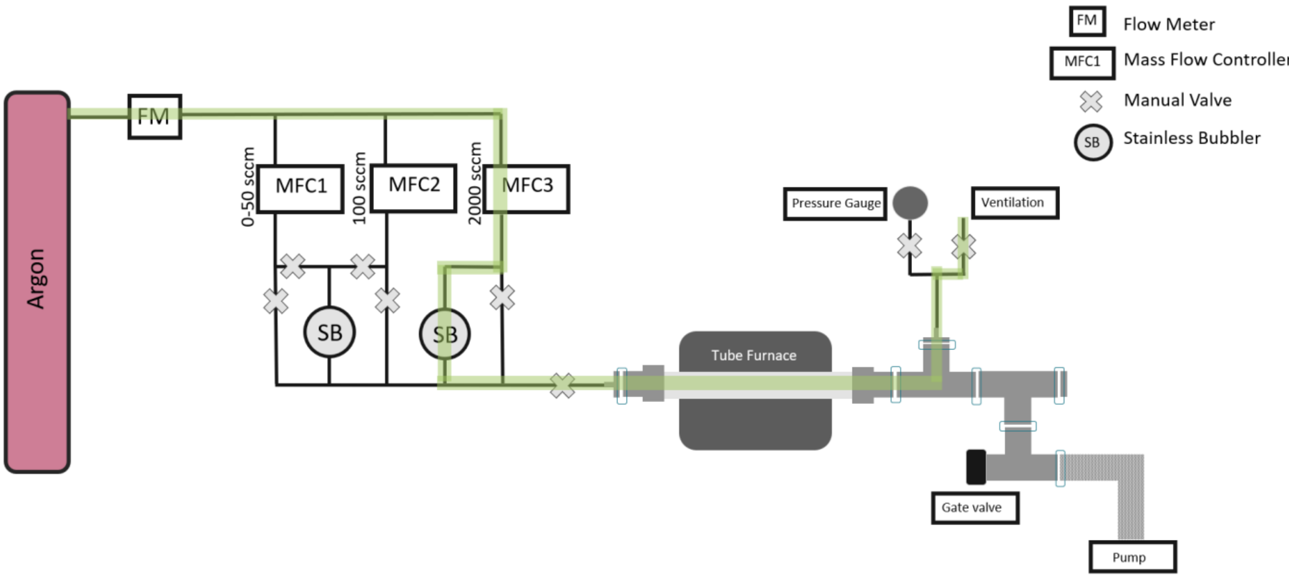

Figure 28: Reaction flow path schematic

3.2 Next Steps

The next steps of this project will be doing experiments with different coating chemistries, modifying the machine for those applications, and recording the results. For initial testing these coatings are applied to silicon wafers so that the coating itself can be analyzed. In the future these coatings will be applied to battery components for performing in situ testing to determine if the coating decreases side reactions within the cell. Initial tests focused on depositing a methyl methacrylate layer using argon as the process gas, but many other monomers can be polymerized using initiated chemical vapor deposition. Other coatings using hydrogen or acetylene as the gas are possible as well and the machine has been designed to support these processes. In using a modular design, the device that can adapt to the research needs of the company and will be a tool used by the designer moving forward. Meanwhile, based on other requests, the machine could be upgraded into auto control system as well.

3.2.1 Characterization

The next steps after coating the samples involve analyzing the coatings and choosing the best processing metrics. This characterization will be done with multiple characterization methods two of which are scanning electron microscopy (SEM) and X-ray photoelectron spectroscopy (XPS).

Scanning electron microscopy or SEM is a technique that uses an electron beam to scan the surface of materials, thus creating a high-resolution image of the surface. Schaeffler has an SEM in house, see Fig. 29, that will be used to analyze the various microstructures of the thin polymer films on the silicon substrate. The SEM will give detailed images of the surface thanks to its nanoscale resolution [9].

Figure 29: Schaeffler's Hitachi SU3800 SEM

Another valuable characterization technique for evaluating nanoscale coatings is X-ray photoelectron spectroscopy or XPS. XPS works by irradiating the surface of a material with low energy X-rays and then analyzing the kinetic energy of the photoelectrons that are emitted to determine the chemical makeup of the sample. We can compare the given energy results to that of a known amount of the given polymer to confirm that the coating has the same characteristics as the bulk polymer.

4. Cost

This section of the report will layout the cost of creating the iCVD machine outlining the various parts, the vendors used to purchase them, as well as the engineering time that has been put into designing the device. For this project there was no set budget, rather the idea was to build a custom device that could not be acquired in a reasonable amount of time for a reasonable cost. The total cost of the parts for this project summed up to be about $19,586. This cost is well below the cost of contracting an outside company to build a custom iCVD reactor.

4.1 Parts

Most of the parts purchased for the design were found using common vendors such as McMaster-Carr or Grainger while some more specialized components such as the vacuum oven and stainless-steel bubblers had to be purchased from companies that specialize in supplying lab equipment. Shown below is a table that has the cost of each part along with its description. Some components were not included in this calculation as they were parts that were already supplied by Schaeffler such as the vacuum pump and the compressed argon tank as well as some hardware that was sourced internally. Some of the purchased items in the costing tables below are tools that were used to fabricate the machine, it is important to note that these tools will be reused in future projects.

Table 1: Tubing cost for iCVD reactor

Product	**Count**	**Cost Per Part**	**Total Cost**
Stainless Steel Tubing for Corrosive Gases Seamless Type 316, 1/4" OD, 0.035" Wall Thickness	2	$ 197.17	$ 394.34
Smooth-Bore Seamless 316 Stainless Steel Tubing 1/4" OD, 0.016" Wall Thickness 6 ft	1	$ 67.74	$ 67.74
24" Long Hose for 1" Tube OD Quick-Clamp High-Vacuum Fitting	1	$ 264.24	$ 264.24
Metal Tube and Conduit Cutter	1	$ 60.09	$ 60.09

Tube Bender	1	$ 177.46	$ 177.46
Copper Tubing with Coated Interior (10 ft)	1	$ 228.80	$ 228.80
Extreme-Temperature PTFE Tubing for Chemicals (10 ft)	1	$ 32.50	$ 32.50
24" Long Hose for 1" Tube OD Quick-Clamp High-Vacuum Fitting	1	$ 264.24	$ 264.24
Extreme-Temperature PTFE Tubing for Chemicals (10 ft)	1	$ 32.50	$ 32.50
CFQ Tube 22mm x 25mm x 24" LG	2	$ 24.25	$ 48.50
CFQ Tube 22x25x48	2	$ 40.40	$ 80.80
CFQ Tube 16mm x 18mm x 12" LG	4	$ 6.25	$ 25.00
Total Cost			**$ 1,676.21**

Table 2: Fittings cost for iCVD reactor

Product	**Count**	**Cost Per Part**	**Total Cost**
Quick-Connect High-Vacuum Fitting for Stainless Steel Tubing Straight Adapter for 1" Tube OD, Trade Number 25	2	$ 158.28	$ 316.56
Ring for 1" Tube OD Quick-Clamp High-Vacuum Fitting	15	$ 10.47	$ 157.05
Quick-Clamp High-Vacuum Fitting Wing Nut Clamp for 1" Tube OD	15	$ 12.40	$ 186.00
Quick-Clamp High-Vacuum Fitting for Stainless Steel Tubing, Tee Connector for 1" Tube OD	1	$ 129.89	$ 129.89
Quick-Clamp High-Vacuum Fitting for Stainless Steel Tubing, Cross Connector for 1" Tube OD	2	$ 168.09	$ 336.18
Cap for 1" Stainless Steel Tube OD Quick-Clamp High-Vacuum Fitting	3	$ 13.04	$ 39.12
Vibration- and Corrosion-Resistant Gauge with Dual Scale Compound, 2-1/2" Dial, 1/4 NPT Bottom Connection	1	$ 36.37	$ 36.37

Yor-Lok Fitting for Stainless Steel Tubing 90 Degree Elbow Adapter for 1/4" Tube OD x 1/4 NPT Female	1	$ 34.72	$ 34.72
Quick-Clamp High-Vacuum Fitting Adapter for 3/4" Tube OD x Barbed Hose	2	$ 33.94	$ 67.88
Quick-Clamp High-Vacuum Fitting for Stainless Steel Tubing, Adapter for 1" OD x 1/4" Yor-Lok OD	2	$ 81.82	$ 163.64
Yor-Lok Fitting for Stainless Steel Tubing Straight Adapter for 4mm x 1/4" Tube OD	5	$ 23.69	$ 118.45
Yor-Lok Fitting for Stainless Steel Tubing 90 Degree Elbow Connector for 1/4" Tube OD	8	$ 27.55	$ 220.40
Yor-Lok Fitting for Stainless Steel Tubing Tee Connector for 1/4" Tube OD	8	$ 38.18	$ 305.44
Yor-Lok Fitting for Stainless Steel Tubing Cross Connector for 1/4" Tube OD	1	$ 72.81	$ 72.81
Front and Back Sleeve for 1/4" Tube OD Yor-Lok Fitting for Stainless Steel Tubing	20	$ 4.31	$ 86.20
Yor-Lok Fitting for Copper Tubing Straight Connector for 1/4" Tube OD	8	$ 8.44	$ 67.52
Yor-Lok Fitting for Copper Tubing 90 Degree Elbow Connector for 1/4" Tube OD	8	$ 15.64	$ 125.12
Yor-Lok Fitting for Copper Tubing Tee Connector for 1/4" Tube OD	8	$ 22.58	$ 180.64
Front and Back Sleeve for 1/4" Tube OD for Yor-Lok Fitting for Copper Tubing	8	$ 5.62	$ 44.96
Quick-Clamp High-Vacuum Fitting for Stainless Steel Tubing, Adapter for 1" OD x 1/4" Yor-Lok OD	2	$ 81.82	$ 163.64
Yor-Lok Fitting for Stainless Steel Tubing	1	$ 34.72	$ 34.72
Quick-Clamp High-Vacuum Fitting	1	$ 33.94	$ 33.94
Yor-Lok Fitting for Stainless Steel Tubing	1	$ 20.26	$ 20.26
Yor-Lok Fitting for Stainless Steel Tubing	5	$ 11.87	$ 59.35

Yor-Lok Fitting for Stainless Steel Tubing	1	$ 72.81	$ 72.81
Push-to-Connect Tube Fitting with Universal Thread	8	$ 2.26	$ 18.08
Yor-Lok Fitting for Stainless Steel Tubing	6	$ 29.25	$ 175.50
Universal-Thread Push-to-Connect Tube Fitting	8	$ 13.76	$ 110.08
Total Cost			**$ 3,377.33**

Table 3: Valve cost for iCVD reactor

Product	**Count**	**Cost Per Part**	**Total Cost**
Gradual On/Off Quick-Clamp Valve 1" Tube OD	1	$ 595.11	$ 595.11
316 Stainless Steel Panel-Mount On/Off Valve	8	$ 147.10	$ 1,176.80
High-Purity Tank-Mount Pressure-Regulating Valve (CGA 580)	1	$ 731.65	$ 731.65
High-Purity Tank-Mount Pressure-Regulating Valve (CGA 350)	1	$ 748.52	$ 748.52
Total Cost			**$ 3,252.08**

Table 4: Main component cost for iCVD reactor

Product	**Count**	**Cost Per Part**	**Total Cost**
FMA-1605A MASSFLOW METER 2 SLPM 0-5V	1	$ 1,496.49	$ 1,496.49
FMA-1617A MASSFLOW METER 100SCCM 0-5V	1	$ 1,496.49	$ 1,496.49
FMA-1604A MASSFLOW METER 50SCCM 0-5V	1	$ 1,672.15	$ 1,672.15
Thermocouple Probe for Surfaces	1	$ 27.54	$ 27.54
BRISKHEAT Heating Cord: 0° to 482°, 36 in Lg, 0.1875 in Wd, 120 V Volt, 64 Watt	1	$ 81.24	$ 81.24

WESTWARD Drawer Bin Cabinet: 17 3/4 in x 7 in x 9 3/4 in, 13 Drawers, Stackable, Polystyrene, Black	1	$ 25.27	$ 25.27
Thermo Scientific Tube Furnace	1	$ 4,094.57	$ 4,094.57
Little Giant Welded Mobile Workbench	1	$ 1,079.58	$ 1,079.58
Vibration- and Corrosion-Resistant Gauge with Dual Scale Compound, 2-1/2" Dial, 1/4 NPT Bottom Connection	1	$ 36.37	$ 36.37
Stainless Steel Bubbler for CVD Liquid Precursors (150ml) - BL-SS	2	$ 635.55	$ 1,271.10
Total Cost			**$ 11,280.80**

Summing the total cost from each table, the calculated grand total for all parts is $19,586.42.

5. Codes and Standards

Codes and standards are important when designing engineering projects, especially when dealing with potentially hazardous materials such as lithium metal and other battery chemicals. As stated earlier, lithium metal is extremely reactive and is usually worked with in a dry, argon-filled glovebox to prevent reactions with the air. Another material used in the battery lab is sulfide based solid electrolyte, which when it encounters moisture in the atmosphere, creates hydrogen sulfide, a gas poisonous to humans. Taking precautions to understand and prevent these dangers are paramount to the safety of the researchers in the lab.

The National Institute of Standards and Technology has created a standard for compressed gas safety labeled NIST S 7101.61 [10]. This standard goes through the best practices when using compressed gas so that safety is maintained. For example, line 401 states that "Cylinders shall be secured at all times to prevent them from falling or being knocked over by securing them to a gas cylinder cart, framework, or fixed object by use of a restraint". This statement was considered during the design of the system and was accomplished by mounting a bottle holder to the side of the steel cart that has nylon straps to hold the bottle, keeping it securely fixed to the cart in an upright position. The mount has locations for two bottles, each with a fastener to individually secure the bottle, per line 403 of the standard. Later, in line 473 of the document, it is stated that "Cylinder pressure shall be reduced through a regulator mounted to the cylinder-valve outlet or through a manifold". This was also factored into the design and two regulators were purchased, one for use with inert gases like argon, and one for use with flammable gases such as hydrogen.

Another standard that was followed in the design of the reactor is the ANSI/ASHRAE standard 62.1-2019 [11], which describes the minimum ventilation rates for acceptable indoor air quality. The polymerization process releases gases that could be harmful for humans to breathe. This is why the machine is designed to operate in an area with a ventilation arm and an adequate exhaust tube.

6. Societal, Ethical, and Environmental Concerns

The potential for this project to have a net positive effect on society is largely based in it's potential for furthering the efficacy of metallic anode solid-state batteries, one of the most promising cell chemistries we have seen. Developing these polymer coatings to prevent negative side reactions could be the innovation necessary to make metallic anode solid-state batteries viable for mass production. This would have huge impacts on many markets, namely the automotive market.

A metallic anode ASSB pack would provide a large boost in total pack energy density, meaning that a vehicle of the same pack weight would be able to travel a much longer range without needing to be recharged. This also works the opposite way, so a lighter pack would have the same range as today's standard liquid electrolyte lithium-ion packs, thus increasing the efficiency of the entire system. This not only could save energy, but it will also allow vehicle manufacturers to build cars with longer ranges. Another advantage of moving to ASSB packs is that they are nonflammable, unlike their liquid electrolyte siblings. This increased safety along with longer range are sure to increase the number of consumers that switch to battery and hybrid electric vehicles.

This shift in the consumer base will decrease the overall vehicle greenhouse gas emissions, helping us push towards a state of carbon neutrality. As we know, density is equal to mass divided by volume meaning that an increase in energy density will also have an inverse impact on the volume of battery packs, allowing for more elegant engineering solutions.

Another advantage of going solid-state is having the capability to fast charge cells due to their stability and nonflammable nature. Developing these coatings successfully could stop possible side reactions within the cells, allowing fast charging, thus giving EVs a similar energy refill time to that of ICE cars. With substantially less maintenance, more range, and similar refill time to combustion vehicles, ASSBs give the consumer a new choice for mobility.

As more research is being done in the field of lithium-ion batteries, environmental and ethical concerns are being raised about the mining practices used to harvest lithium metal. A large amount of the lithium comes from Argentinian and Chilean salt flats. This process uses a large amount of freshwater, which is not ideal. In China and Australia, battery-grade lithium is exposed to large amounts of heat to purify it, which is extremely energy intensive. In other parts of the world however, new techniques are being used to harvest lithium, such as the projects in Germany and the UK that filter lithium from hot brines beneath granite rock [12]. This process has the possibility of yielding zero-carbon lithium, which would be a good way to preserve the environment while harvesting the very material that can propel energy storage for the next generation.

7. Conclusion

For this industry sponsored project, the task was to create a mobile iCVD system that could be used for the creation and characterization of polymer films in battery components. First, the topic of iCVD and iCVD reactors was thoroughly researched to understand the challenges that would be faced. This knowledge was then used in a hands-on scenario at the University of Akron, using their iCVD reactor to better understand the process. The concept was then sketched out based on decided requirements for the machine. Next the concept design was finalized, and parts were selected based on necessary machine parameters. The parts were then assembled along with some adapters that were created to complete the machine build. Moving forward this device will be used to determine the optimal nano scale coatings for battery components.

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