CHAPTER 1 SCOPE AND OTHER RESOURCES

1.1 SCOPE OF THIS BOOK

Products requiring vacuum technology touch almost everyone's life every day. Consider the automatic thermostat adjusting the temperature in your house, the light-emitting display in your alarm clock, the vacuum packaging for your breakfast food, the satellites providing the weather forecast to download on your phone, the phone itself, the GPS systems indicating the morning traffic, the coated sunglasses keeping you safe as you drive into the sunrise, the insulated cup keeping your coffee hot, and finally, the system(s) providing workplace security. Thus, even before the workday has begun, most of us probably use at least ten products that would not be possible without vacuum technology.

There were about 20 million people working in high technology in the U.S. in 2018 (about 16% of the U.S. workforce, see the U.S. Bureau of Labor Statistics website). Even if only one in every ten of these technologists use some sort of vacuum technology, that means between 1 and 2 million U.S. workers need a reasonable understanding of this technology area. In comparison, 1–2 million workers is also about the number of farmers and ranchers in the U.S., many of whom also use vacuum technology (e.g., milking machines for dairy, harvesting machinery for delicate fruit, etc.). Although all of these vacuum-enabled processes are rapidly advancing, this book is designed primarily to overview vacuum technology for individuals working (or preparing to work) in the "high-technology" sector. This includes not only commercial technologists and students being introduced to vacuum research for the first time, but also managers who need to understand vacuum technology enough to make critical decisions related to their company's or laboratory's vacuum equipment and personnel infrastructure. Although these broad group categories often have a different understanding of the science behind vacuum technology, the goal of this book is to be understandable and useful to the broadest possible range of readers.

This book, "Overview of Vacuum Technology," aims to provide the reader with improved understanding in four main areas. The combined goal of these four general areas is to provide the reader with a broad understanding of how to effectively use vacuum equipment so that it meets the needs of research and/or commercial products.

1. Develop insight of how gas molecules act at low pressure. The goal here is to help the reader to "think like a gas molecule," and so consider how molecules in a vacuum can collectively influence a process or product.

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Overview of Vacuum Technology, Timothy A. Gessert

2. Review *typical* components used in vacuum technology. This area encompasses the largest part of this book and aims to provide the reader with an understanding of the basic "toolbox" of the vacuum technologist.
3. Indicate current directions where component evolution is rapidly occurring. This area is aimed at providing a foundation between the present job duties of a vacuum technologist and likely future changes to these duties.
4. Finally, provide a foundation to understand "cost of ownership" concerns. This broad area includes guidance related to both initial purchase costs as well as the costs related to the less-quantifiable areas, such as operation and maintenance. For the new vacuum technologist, this last area is often the most important, providing a foundation to appreciate how to produce samples or products with a desired level of reproducibility, while maintaining the vacuum equipment within the available production and/or research budget.

The reader should remember that this book is only an "Overview," and more specifically, an overview largely associated with the types of vacuum systems and components that are typically used in modern semiconductor processing and related materials development. This is a very narrow segment of the much broader landscape of technologies and products impacted by vacuum systems and components. For example, this book will only lightly touch on aspects related to the extensive use of vacuum systems in medical fields, food processing, and product transportation. Likewise, the very central role of vacuum technology in the rapidly evolving areas of particle beams, fusion research, and space simulation/exploration will not be addressed in any detail. Nevertheless, the information presented here will certainly relate to these areas and will, hopefully, provide the reader with guidance to pursue additional information relevant to these fields. Regarding additional information, the book will indicate where some additional and topic-relevant information may be found. In many cases, this information will relate to printed literature and/or websites. However, for a reader relatively unfamiliar with vacuum technology, the importance of face-to-face discussions and/or formal training will also be highlighted and strongly encouraged. This is because most commercial or research vacuum systems are similar to modern automobiles; they are, generally, very complex systems and are difficult to outline sufficiently in any overview format.

1.1.1 Relevant background of the author

The author of this book has been involved with mentoring undergraduate and graduate students in many aspects of vacuum technology for semiconductor materials and device research for over 30 years. He has further provided instruction for many hundreds of vacuum technologists working in both private industries and public institutions (e.g., universities and national/international laboratories). Much of this instruction has occurred through teaching short courses offered by professional organizations such as the American Vacuum Society (AVS) and the Society of Vacuum Coaters (SVC)—both societies are affiliated with the American Institute of Physics (AIP). The instructor has also provided "face-to-face" instruction and consulting at production and research sites where vacuum processes are being performed. All these interactions have provided a unique opportunity to gain first-hand knowledge of the level of vacuum-process understanding that often exists on actual production floors or research labs as well as within other locations within corporate or academic institutions. Because many institutions have been observed over many years, the author has also gained insight into how (and why) core understanding of vacuum technology can be significantly impacted as a workforce naturally evolves over time (i.e., production relocations, personnel retirements, product consolidations, etc.). Finally, for many years, the author has been an Associate Editor with the scientific journal *Thin Solid Films*. In this capacity, he has overviewed many hundreds of scientific manuscripts that describe materials science and developments related to vacuum-processed thin-films and interfaces. All of these experiences have provided the author with a perspective regarding the typical level of technical and scientific understanding available to individuals new to vacuum technology.

Because this book has been written with the intent of being understood by a broad group of vacuum technologists, many of the technical and/or scientific descriptions are provided with either a minimum of mathematical foundation or in a simplified mathematical form. Examples are presented that can often embody more complicated concepts than are immediately apparent. In these cases, references are provided to help guide the reader toward deeper understanding. The content is also designed to indicate pathways toward developing "best practices" in vacuum technology. However, some examples are also provided to illustrate where poor choices can be made or where often-used vacuum practices can lead to non-reproducible results. It is hoped that, by illustrating both "good" and "not-so-good" practices, the reader may recognize some of their own experiences and consider what steps may be taken to improve future results.

This book primarily describes the types of vacuum technology and related processes that are used in the semiconductor industry. There are several reasons for this approach. First, the semiconductor industry presently represents one of the largest fractions of users of vacuum technology, and so, many of the technologists and students reading this book are likely to be either presently working in, or training for, occupations in this industry. Second, because so much vacuum equipment is produced for the semiconductor industry, much (if not most) of the recent advancements and standardization directions for vacuum components have been driven by this industry. This means that the first step in selecting a particular vacuum component is often to first understand the *semiconductor requirement* that the component design may be trying to address. For example, one important area of concern in the semiconductor industry is reducing the potential for contamination from both vapors and particles. Appreciating this requirement helps to explain certain product options in both component cleanliness and surface conditioning as well as various designs options—such as those related to high-speed bearings in turbomolecular pumps. Finally, because of the substantial volume of vacuum products used by the semiconductor industry, technologists in other vacuum-related fields can often identify semiconductor/vacuum products that not only meet (and often exceed) their present requirements, but may do so at a cost much lower than products that may be designed for a smaller non-semiconductor market. This is especially true if an end user has the ability to consider using pre-owned semiconductor vacuum equipment in their process. For all of these reasons, focusing this book on the needs of the semiconductor industry is viewed as a reasonable gateway for a general discussion on vacuum components and related processes.

1.1.2 Additional resources for vacuum technology information

Guidance for additional resources would have historically been provided through other published books. Although many of these references are indicated in this book, it is also important to remember that other sources of quality information are readily available. These include not only traditional journals (e.g., Journal of Vacuum Science and Technology A&B, published by the AVS) and professional periodicals (e.g., Physics Today, Vacuum Coating and Technology), but increasingly, also incorporate quality websites that are often produced by vacuum-component or vacuum-system manufacturers who have detailed and up-to-date knowledge of their components and technologies. Many professional societies, including the AVS and SVC, also develop and offer vacuum *short courses* at local, national, and international conferences as well as customized "on-site" vacuum courses at industry locations. Finally, these and other societies are expanding experimentation with "virtual" vacuum courses that can be offered on-line. Although these virtual courses may not embody all the benefits of face-to-face interactions, they can be effective alternatives if small group sizes or remote production locations limit more traditional options.

With so many information sources available to vacuum technologists, a question is often asked, what is the importance of the traditional reference "textbooks" related to vacuum technology? One answer often used is the following: There have been many excellent vacuum technology and science reference books published since its rise to commercial importance starting in the 1950s. Most of these books provide detailed discussions of the mathematics and physical principles, and collectively form a solid technical foundation for this increasingly critical technology. For this reason, the new vacuum technologist is *strongly encouraged* to develop a library of as many of these historic reference texts as possible. Some useful titles are provided in the reference section (Guthrie, 1963; Roth, 1990; Hucknall, 1991; Delchar, 1994; Hablanian, 1997; Chambers *et al.*, 1998; Hoffman *et al.*, 1998; Lafferty, 1998; Tompkins, 2002; O'Hanlon, 2003; Outlaw and Tompkins, 2009; Jousten, 2016; and Suumeijer *et al.*, 2020). Also, vacuum component manufacturers often publish their own literature addressing general vacuum technology (Umrath, 2007, 2013). In addition to purchasing new copies of these books, acquiring used (and often out-of-print) vacuum textbooks represents another important option. Creative options to acquire used textbooks can include alerting institutional library staff to advise when/if reductions in vacuum textbooks are planned as well as letting retiring colleagues with established book collections know that you would be interested in *inheriting* some of their vacuum technology books if they discover that their home bookshelf space (or their spouse) is not necessarily welcoming the influx of vacuum textbooks. Regardless of how vacuum reference texts may be acquired, their detailed content often goes well beyond the needs of most novice vacuum technologists. For these individuals, quickly acquiring a broad appreciation of why certain components have been engineered for certain types of vacuum process equipment is generally more important than, for example, being able to precisely calculate the effects of small changes in systems or component design. It is for the needs of these novice vacuum technologists that this book is designed.

Regarding other important sources of vacuum information, first and foremost is to remember that nearly all novice vacuum technologists work near more experienced colleagues. In vacuum technology, as in most other endeavors, the experiences of these other colleagues can be priceless in saving you time and effort. Talk to your more experienced colleagues, find out what types of vacuum (or other) technical systems they have worked on in the past, and how deeply into the "nuts and bolts" of these systems their previous experiences may have taken them (if you have not realized it yet, technologists generally enjoy talking about their past work!). However, also keep in mind that the quietest people are often the individuals with the most useful information and experiences. In this regard, do not be surprised if you have to explain (possibly with some embarrassment) *what you do not know*—to get your colleagues to fully appreciate—*what they do know and can help you with*.

Perhaps the second most important information source is manufacturers. Get to know the manufacturers of your particular vacuum equipment and get in the habit of writing down questions to ask them when/if you talk to them in the future (especially those questions that your *experienced colleagues* admit they cannot answer fully). If the questions need an answer quickly, the best route often is to pick up the phone, call the respective company, and ask them to connect you with "technical customer support." Remember, vendors are in the business of selling vacuum equipment, and they want almost nothing more than to have customers in the field who believe their company can clearly and usefully answer a customer's technical questions. Remember also, if you are relatively young *and* new to vacuum technology, then vendors generally *really want to talk to you* even more so than your more experienced colleagues. This is because the vendor has the opportunity to convince you to become a customer for a very long time—and well after some of your more senior colleagues have retired! Remember, although you may not have much experience with vacuum technology, or much money to spend on vacuum systems or components now, both these things will change with time. You are the future of vacuum-component suppliers and they know their long-term success depends partly on providing useful answers to their youngest customers.

The final key source of technical information is becoming associated with professional societies, such as the AVS or SVC (and similar and/or associated societies within and outside of the U.S.). These societies not only organize specialized training on vacuum processes and technology, but also sponsor related web-based technical talks (of short duration), webinars (of longer duration), local meetings, and larger national and international conferences. Most technical societies also provide considerable technical content on their websites. Much of the web-based content is free, while some may require society membership (meaning a small annual membership fee—or an even smaller membership fee if you are a full-time student!). When/if attendance to a local or larger conference can be arranged, this can represent an unparalleled opportunity to talk to experienced technologists outside of your immediate company or educational institution. It also provides an important opportunity to talk to dozens of vacuum-equipment vendors. Even for very experienced vacuum technologists, talking to company representatives at a *vendor exhibit* is nearly always insightful. This is because not only are the vendor sales staff available for questions, but more importantly, many companies will also have present some of their product-development scientists and engineers (i.e., the engineers and scientists who often invented the products you are using). Talking collectively to all of these people, in person, and at the same time, will often answer not only your immediate questions, but possibly answer questions on vacuum issues you did not even know you had.

1.1.3 Comments on understanding vs operating vacuum systems

There are three broad considerations to effectively use vacuum technology in production or research: (1) understanding how the various components of the vacuum system are designed to work and their inherent limitations; (2) understanding how to operate the vacuum system so it has the best chance to perform processes with an expected degree of reproducibility; and (3) understanding what maintenance activities are needed to meet production or research requirements. Although these broad considerations may seem obvious and/or simplistic, interactions between these considerations are often not appreciated by the new vacuum technologist. One reason for this is because the historic activities of the vacuum technologist have become much more *segmented* in modern society. To put this another way, not so long ago it would have been common for the designer of the vacuum system to also be its builder, its vacuum-process developer, and ultimately its operator. In this scenario, one person (or perhaps a small team) would have been involved in developing nearly all aspects of the vacuum hardware and related processes. The communication needed to optimize these separate job functions would have progressed naturally. In contrast, for many modern production or academic situations, design, procurement, construction, process development, and system operation are more often separate "job functions." In this modern case, the communication needed to optimize the various aspects of a final vacuum process requires both good communication and technical understanding *by all parties involved*. More often, a new vacuum-system operator or student may be introduced to vacuum equipment that was designed and optimized by many other people before them, and possibly many years ago. This new technologist will not have much initial awareness of the design of the system, its multiple components, or how the evolution of these components might impact the vacuum product or research. The primary guide for the new technologist is often a single question—does the product meet a specification—or to what degree can a scientific result be reproduced? Similarly, when a new vacuum engineer designs and/or constructs a vacuum system to be operated by others, their primary input to how various components may affect the overall system or process may be only during "initial testing." These initial tests often do not indicate longer-term product/process reproducibility changes that can occur due to component evolution or system maintenance. For all these reasons, the new vacuum technologist is *strongly encouraged* to seek out those who have been previously involved with the system or process design, or in the case of the designer, seek out those who will be later involved with the operation of the vacuum hardware and/or processes.

The interrelationships between vacuum components and processes described in this book will be the ones most often seen. This is not to infer that these are the only ones, but rather intended to give the reader a "feeling" of how the function of many different components may combine to affect vacuum-process reproducibility. As one simple, typical example, consider putting a product or sample into a vacuum chamber and then pumping the chamber to a pre-determined "process base pressure." In a well-designed vacuum process, the required process base pressure was likely determined by a combined knowledge of the tolerance of the process to known residual contamination, a rate of process deposition and/or erosion, the ability of the system components to achieve a significantly lower "ultimate system base pressure," and the time that can be reasonably "invested" for pump down. The operator or student is usually advised that as long as a specific "process base pressure" is achieved, the product/result should be sufficiently reproducible. Nothing could be simpler—right? Well, not so fast… What if the vacuum chamber was left open considerably longer than usual? What if the chamber is opened on a very humid summer day, while the initial process testing was done in the dead of winter (i.e., on a lower humidity day)? What if the facility cooling water is 5 °C colder today than yesterday (so the chamber walls will be colder)? What if the cleaning process used for the sample was changed (and different cleaning solutions may have different outgassing characteristics)? What if a replacement vacuum gauge was installed during maintenance (is the indication of the new gauge actually representing the same gas density)? What if the turbomolecular pump was replaced yesterday due to an immanent bearing failure? What if the cryogenic pump was regenerated last night? All of these, and many other external or internal parameters, can significantly affect both the time it may take to reach the "process base pressure" as well as the reproducibility of the following vacuum process. Moreover, these parameters can also affect the final vacuum-process result—even if the time to reach base pressure was as expected! Indications of many of these component and process variations will be presented and discussed in this book with a view toward guiding the reader to develop a feeling of how these individual and/or combined process variations can influence the results of a vacuum process.

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