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# Process Variations in Microsystems Manufacturing

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*Dedicated to my loving wife, Deanna.*

# Preface

The main theme of this text is to explain the methods used to estimate and manage the device parameter variations that result from using microsystems manufacturing methods. The broadest definition of microsystems includes devices implemented using any semiconductor-based micro- and nano-fabrication techniques, including silicon integrated circuits (ICs), micro-electro-mechanical (MEMS), photonics, nano-electro-mechanical (NEMS), non-silicon integrated circuits, and others. Nevertheless, the focus of this text is on the class of microsystems devices called MEMS (and NEMS[1]). The words "microsystems manufacturing" were purposefully selected for the title due to the fact that the major topics covered herein are also generally applicable to all of the other types of microsystems technologies.

A companion volume on microsystems manufacturing is directed to the topic of *process integration* techniques for MEMS devices. Managing process variations and process integration are both complex issues, and therefore, it is believed that each of these areas deserves a sufficiently comprehensive coverage in the form of a dedicated volume in order for the reader to fully appreciate and understand these topics. Both of these subjects are critically important for engineers to understand in order to be successful in the development and production of MEMS or any other type of microsystems.

There are several reference books and handbooks that have become available over the past decade that describe the fabrication methods that are commonly used in the implementation of microsystems technologies. Notably, many of these texts cover a number of individual processing steps used in the fabrication of

[1]MEMS and NEMS will be grouped together under the term "microsystems" and used throughout this book to describe the collective of devices and systems that are manufactured using both micro-scale and nano-scale fabrication methods. The reasons are as follows: First, it can be difficult to differentiate these technologies from one another solely based on the dimensional feature sizes. Second, it is awkward to use both the combined term "micro- and nano-systems" as a label for these technologies. Third, and perhaps most importantly, all of these technologies basically use the same set of fabrication techniques regardless of the exact feature sizes involved.

microsystems devices and go into some depth to explain the basic physics behind each of these processing steps. Therefore, a valid question is whether new books are needed or desirable.

The answer to this question is “yes” since the existing references mostly fail to adequately cover two extremely important topics related to manufacturing of microsystems, namely, how to estimate and manage the resultant device parameter variations that are a result of the manufacturing processes used with the purpose of obtaining acceptable production yields (i.e., percentage of number of working devices meeting the performance requirements out of total number of devices made) and how to take a series of individual processing steps and combine them into a process sequence such that the production yields are acceptable.

Process variations are the differences in the dimensions and material properties of the devices being produced from the desired ideal values developed as part of the device design. While every manufacturing operation strives to replicate devices with exacting control of the dimensions and material properties, in reality, each device made will have slight and often measureable differences in the parameters. Surprisingly, this topic is rarely, if ever, mentioned in existing microsystems books despite the fact that it is an exceedingly important issue. One of the reasons for this omission is that there is a widely held misconception that fabricating small devices equates to high-precision manufacturing. This is not true. Instead, when the dimensional variations of the device’s critical features are expressed as a ratio of the desired value of the same feature, microsystems fabrication methods are almost always comparatively worse than macroscale production techniques, and they also tend to degrade, as the dimensions get smaller.

With respect to material properties, they also exhibit variations due to slight differences in the processing conditions across the substrate and across the batch of substrates. Moreover, some of the important properties of the materials used in MEMS microsystems are very dependent on the manufacturing process sequence and processing steps used in the implementation. And since most MEMS process sequences are highly customized, there can often be no a priori knowledge of the resultant properties of materials used in the development of MEMS devices.

The consequence of these variations is that if the dimensions and the material properties have variations from their “as-designed” values, the output behavior and performance of the device will also have a variation in its behavior. Furthermore, variations in the device output may result in the device not working or not meeting the required performance specifications. The outcome will likely be wastage of manufactured devices, higher production cost levels, and lowered performance levels.

Part of the reason the topics of process variations and process integration have not been previously been given much attention is that many types of microsystems technologies, such as MEMS, are relatively new and are only recently being successfully commercialized. Therefore, the knowledge of manufacturing issues for the production of MEMS is relatively limited. Additionally, academic researchers have authored many of the previous books on microsystems fabrication methods and rarely focus on the more detailed manufacturing issues.

The major goal of this book on the topic of process variations is to provide the readers with an adequate understanding to allow them to perform the following:

1. Estimate the manufacturing variations of the processing steps and process sequences used in the production of a microsystems device.
2. Recognize what metrology methods are suitable for evaluating whether processing steps performed are acceptable or not.
3. Evaluate the impact of manufacturing variations on the resultant microsystems device output behavior and performance.
4. Estimate the functional and parametric yields of microsystems manufacturing process sequences.
5. Track and analyze important metrics for ensuring that production steps are meeting pre-defined standards.
6. Understand how to modify the design of a microsystems device taking into process variations such that the yields will be acceptable in production.

This book is intended for practicing engineers and scientists working in microsystems development as well as students who are training for employment in the microsystems industry. The prerequisites for understanding this book are a basic knowledge of engineering, math, and physics. Knowledge of fabrication methods is not required but may be useful since these topics are briefly reviewed. While the material is mostly focused on MEMS manufacturing, it is important to state again that the issues of process variations is equally important to other types of microsystems. Therefore, readers working on these other microsystems technologies can also benefit from the material in this volume.

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Any errors or omissions are my fault alone, and the opinions expressed herein are mine and do not necessarily reflect the views of CNRI.

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