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Chemical risk in early design

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CHEMICAL RISK IN EARLY DESIGN

by

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ABSTRACT

The purpose of this thesis is to present a methodology to identify risks in the chemical product development process, including fortification of the failure mode taxonomy by including chemical failures. This work will enable comprehensive risk analysis in technology-based products that have a chemical based subsystem, such as those used in the lithography process in the semiconductor industry. This research broadened the failure mode taxonomy by identifying chemical failures from publications in the semiconductor industry. These failures were analyzed to determine the rudimentary failure modes in each case. The newly identified failure modes were added to the failure mode taxonomy. The taxonomy was then verified by generating potential risks of a chemical based product through the use of a case study. The case study analysis verified the research by producing the failure mode listed in the publication.

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SECTION

1. INTRODUCTION

The purpose of this research was to present a methodology to identify risks in the chemical product development process. Chemicals become materials and then parts that combine to create value for the end user, and in many cases the product value comes from the basic material design. Chemists and engineers make decisions when designing new chemicals early in the design process. The effect of these decisions can be learned through empirical testing, usually in the integration or prototype phase of design. Waiting to learn the risks and their consequences later in the design process can be expensive if design changes are needed. This is further emphasized if inexperienced scientists and engineers are making the decisions early in the design process.

The semiconductor industry produces a large number of computer chips, including microprocessors, to memory, to integrated circuits (ICs), system on a chip (SOC), and more. The use of chips ranges from common home appliances, such as dishwashers and microwaves, to more complex systems, such as, tablet computers and servers. The microelectronic devices that power and control the larger electronic devices incorporate several chemicals.

This connection of chemical design, their use in microelectronics and the long design chain lead to this research. The goal was to both fortify the failure mode taxonomy to also include chemical failures and then to present a methodology to identify risks in the chemical product development process. This will enable comprehensive risk analysis in technology based products, specifically focusing on the semiconductor industry.

PAPER

I. Chemical Failure Mode Addition to the Failure Mode Taxonomy

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Abstract

The research objective of this paper is to fortify the failure mode taxonomy by including chemical failures. This inclusion would enable comprehensive risk analysis in technology-based products. As technology improves at an exponential rate, partially due to chemical advances in the semiconductor industry, failure identification tools must keep up with the pace. While the current version of the failure mode taxonomy does consider multiple domains of failure, it does not include a comprehensive collection of chemical failures. Therefore this taxonomy is insufficient for a large number of new products. The research presented here includes identifying chemical failures from publications in the semiconductor industry. These failures were then analyzed to determine the rudimentary failure modes in each case. Finally the newly identified failure modes were added to the failure mode taxonomy. A case study is presented to demonstrate using the updated failure mode taxonomy to identify both potential failures and product risks.

Introduction

The research objective of this paper is to fortify the failure mode taxonomy to also include chemical failures, which will enable comprehensive risk analysis in technology based products, specifically focusing on the semiconductor industry. The semiconductor industry produces a large number of computer chips, including microprocessors, to memory, to integrated circuits (ICs), system on a chip (SOC), and more. The use of chips ranges from common home appliances, such as dishwashers and microwaves, to more complex systems, such as, tablet computers and servers. The broad use of computer devices in modern society, coupled with a global market, supports the $323.3 billion market worldwide [1].

The capability of a chip is associated with its processing speed. The release of more sophisticated products depends on how fast chips operate. The rate of semiconductor technology development is often modeled following Moore's Law [2]. Moore's law is a model that states that every two years, the number of transistors on an individual chip will double [2]. The semiconductor industry has followed this law for decades. Moore's law has subsequently driven a smaller, faster, cheaper approach to both chip design and manufacturing. Further, a smaller, faster, cheaper approach has been enabled by advancements in both tools and materials for patterning devices. Much of the material development has centered on chemicals and their use in the lithography process. The lithography process, similar to a negative producing a photograph, produces the logic patterns used to make devices. Fundamentally, lithography is a series of chemical transformations that, together, create a pattern. This pattern is used in the manufacturing of integrated circuits [3]. The smaller the patterns, the more transistors can be built in the same area, thus increasing both the processing speed and the memory capacity [2]. However, these small patterns are susceptible to failures that are in the same small scale.

A gate oxide separates the gate terminal from both the source and the drain in a transistor, thus serving as a dielectric (see Figure 1). A voltage is applied to the gate, allowing electrons to flow from the source to the drain through a channel both between the two and under the gate. If the gate oxide is too thin, electrons can channel through the oxide to the gate, causing current to leak through the device, resulting in electrical failure of the transistor. A dramatic example of a failure at a small scale is Intel's recent issue with the Sandy Bridge graphics processor chip. This chip failed due to a gate oxide that was too thin, resulting in the current leaking [4]. In 2001 roughly 8 million chips shipped from Intel were fabricated with a gate oxide that was too thin. This failure mode cost Intel $300 million in lost sales and $700 million in repairs [4]. The failure of this chip emphasizes how a failure can progress through the design process, consuming resources until it is identified.

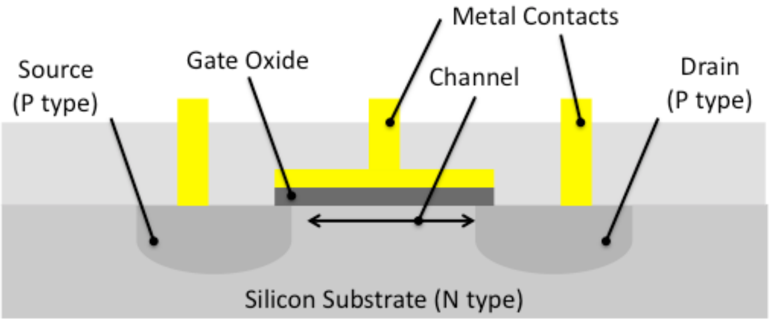

Fig 1 Semiconductor transistor design

A variety of chemicals are used to make semiconductors. This paper focuses on the failure modes of lithography process chemicals. Most advances in the lithography process have come from researching the polymers used to make liquid chemicals that are spin-coated onto a substrate [5, 3]. These chemicals range from photoresists, which are photoactive coatings used to retain a pattern, bottom anti-reflective coatings (BARCs) used to attenuate light, hardmasks used to transfer a pattern, and spin-on carbon (SOC) layers that provide further pattern transfer capabilities [3].

Currently, the failure mode taxonomy addresses only mechanical and electrical failures. Therefore, using it to guide risk assessment, as it is intended, cannot lead engineers to predict such failures as the Sandy Bridge graphic chip failure. To understand risk and mitigate failures, the failure mode taxonomy must include chemical failures. Academic publications were analyzed to identify both failure causes and modes of chemical failures in the semiconductor industry to fortify the failure mode taxonomy to include chemical failures.

Background

Several risk assessment methods are currently used in the chemical industry, some of which are drawn from the Occupational Safety and Health Administration (OSHA) PSM standard Title 29 CFR 1910.119. This federal regulation requires chemical plants to conduct process hazards analysis (PHA) [6]. PHAs are methodologies that follow systematic approaches to find both hazards and deviations, and are defined by OSHA as a systematic effort designed to identify the significance of hazards associated with either the processing or handling of highly hazardous materials [6]. The regulation also includes a PHA as a method to provide information, which will help both employers and employees make decisions that will improve safety [6]. Along with OSHA, many other entities have PHA guidance. These entities are detailed in government regulations such as 21 CFR 120.7, 29 CFR 1910.119, 40 CFR 68, FAA-DI-SAFT-101, DOT-FTA-MA-26-5005-00-01 and DOE Order 5480.30.

During the research, focus was placed on PHAs documented either under OSHA regulations or used within the industry. The PHAs examined in this study, taken from OSHA, included fault tree analysis (FTA), hazard and operability study (HazOp) and failure mode and effects analysis (FMEA). These methods are listed by OSHA as tools that can be used in industry to assist in both determining and understanding hazards and potential failure modes in a chemical process [6]. Fault tree analysis is a quantitative method that uses binary logic to understand how a failure propagation occurs [7, 8]. A hazard and operability study, or a hazard and operability review, targets chemical production processes; these studies are semi-quantitative [9, 10]. FMEA is a quantitative method designed for products with several parts, such as automobiles [11]. FMEA in particular is very common in the semiconductor industry because semiconductor devices are used in automobiles, and for many years there has been a drive to follow standards connected to the automotive industry, including FMEA recommendations [11].

Additional risk assessment tools used in industry, such as event tree analysis, layer of protection analysis, and risk in early design, were also reviewed. These risk analysis methods have published use in industry, addressing some of the limitations of the OSHA listed PHAs. Both event tree analysis (ETA) and layer of protection analysis (LOPA) have been used in the chemical industry. Event tree analysis, similar to FTA, is a quantitative method that uses binary logic to understand how a failure propagation occurs [7; 8]. Layer of protection analysis targets chemical production processes and is semi-quantitative [9; 10].

Risk in early design (RED) is a contemporary risk assessment approach with broad applications across numerous industries. RED uses quantitative methods to analyze both risks and potential failures. RED is the most recent method, and was created to address the intrinsic knowledge requirement most previous methods faced [12, 13]. Each will be reviewed in this section with a focus on how they support the lithography chemical research in the semiconductor industry.

OSHA PHAs

FTA is an analysis technique that starts from a top event. Then determines how a failure could have been caused by lower level events; FTA looks backwards into what could have caused the top event [14]. Both logic gates and common symbols are used to define these event types, much like a flow chart [15]. The probability of the top event is then calculated from the basic event probabilities of the particular tree structure, which adds quantitative value to an FTA [16, 15]. An FTA is helpful because it allows an engineer to see how a series of events could connect and cause a failure. An FTA is also good because it provides a clean view using a tree and thus helps with the complexity of a chemical system. The usefulness of an FTA has been incorporated into the chemical industry, focusing on chemical plant operations [17, 18, 19]. An FTA, however, would be very difficult to complete before a chemical product is mature as several unknown outcomes of the chemical process would need to be researched. Additionally, FTA focuses only on one top event at a time, which means an entire tree must be generated for a top event. This approach becomes very cumbersome when trying to evaluate a complex product that may have multiple failures [20].

HazOp is another commonly used method that helps identify hazards. During HazOp, a knowledgeable team gathers and follows a structured list of guide-words to analyze a process [21]. Through a series of meetings, the team works through the process' piping and instrumentation diagram (P&ID) to evaluate potential issues, their causes, and possible solutions [15]. When a HazOp is complete, the entire process has been evaluated and processes that deviate from the desired situation were examined. This level of detailed analysis helps to thoroughly document and understand how a chemical process works. However, much like a LOPA, HazOp focuses on the chemical production process, and not the early research stage in which the chemical is developed [22, 23]. The

HazOp process requires a team of experts with specialized knowledge and takes a large amount of time to complete due to its thorough nature [22].

FMEA may be the most well-known risk assessment in the semiconductor industry due to the connection between the semiconductor industry and the automotive industry following the QS-9000 quality standard 11. The FMEA process analyzes the intended function of the product and the information is separated into failure effects, modes, and causes [24, 16, 15]. A numerical value is subjectively assigned to the severity, the likelihood of occurrence, and the possibility of detection. These numbers can then be multiplied to generate a risk priority number (RPN). RPNs then helps the team to select the most important areas to mitigate. Both the logical process and the quantitative results have made FMEA an easy tool to use when developing products [25]. The value of a FMEA, however, is limited to the intrinsic knowledge of the team. Typically, a design FMEA is completed later in the design cycle, after product testing knowledge has been gained.

Chemical Industry Risk Assessment Tools

ETA works in the opposite logical direction when compared to FTA. ETA begins with a failure, and then propagates it forward through different binary pathways to a final outcome [26]. The goal of the ETA is to evaluate all the possible outcomes that could come from the initiating event [26]. ETA was first used by the nuclear industry as FTAs were becoming too complex [20]. ETA condensed the analysis into a more concise picture [20]. ETA provides a forward-looking process that identifies all of the possible outcomes by using forward logic. It then analyzes both the likelihood and the consequences that can result from a failure. This method is advantageous because multiple failures can be analyzed allowing the weakness of the system to be identified [27, 28]. However, a very thorough understanding of how something works must first exist so that the parts of an ETA can be built [29]. This is in part because fuzzy math is used to represent subjective judgments [29]. Another drawback to using ETA is that partial failures cannot be distinguished because the system is binary. Much like FTA, ETA only focuses on one initiating event at a time. Focusing on one event at a time would create a very unmanageable approach for a chemical product.

LOPA, as its name implies, is a model that builds separate layers of protection. These different layers serve as barriers to stop the progression of undesirable events [30]. The layers typically start with the chemical process and then progress through internal protections in the chemical plant ending at an emergency response from the community. LOPA is considered semi-quantitative as it does produce a numerical result. The initiating event frequency numbers LOPA produces target orders of magnitude and are considered imprecise [31]. LOPA is focused on chemical plant operations, helping break down complex processes into simple layers so that protection methods can be viewed and general decisions can be made [32]. LOPA, however, requires an experienced, knowledgeable team focusing on only one cause and one consequence [31]. Though LOPA is used in chemical production, it does not address the research stage when a chemical is being developed. In fact, one reference about LOPA recommended that a better method than building layers of protection is to develop a fundamentally better chemical [30].

Contemporary Risk Assessment Tools

The RED method is targeted at identifying risks early in the design process, before a prototype has been built, when the design is still in the concept stage. RED connects either a product's or a process' basic functions, using a functional model, to a historical database of failures using a standardized failure mode taxonomy [12, 13]. This database contains a history of failure modes, their likelihoods, and their consequences. Because the data on product failures comes from historical failures, inexperienced engineers and designers alike can use RED to evaluate their products early in the design phase [12, 13]. The use of matrices provides a simple approach that defines both function and failure combinations that are then quantified by the database by both likelihood and consequence, making RED a quantitative approach [12, 13]. For RED to generate a robust analysis, the historical database must also be robust. Additionally users must be trained to build functional models and interface with the software.

Summary of Risk Tool Application Issues

The product design process must include a design risk tool for the chemical industry, to prevent failures like the Sandy Bridge example. This tool needs to enable potential chemical product failures to be identified and mitigated during the early states of design when it is the least costly to do so. This tool must also be usable for any early stage chemical design process and, thus, must be adaptable to any possible chemical design project.

The above methods [ETA, FTA, LOPA, HazOp] are targeted during the later production cycles instead of early in the design process. Additionally they require a team with both sufficient knowledge and experience to develop a valuable result. These limitations keep risk analysis from occurring until either late in the design stage or, in some cases, all of the way into the production process. The RED methodology was developed to address some of those shortcomings. It catalogs failures corresponding to specific functions in a knowledge base that new designs can be screened against to help assess risk [12, 13]. The product or process must be broken down into a standardized functional model based on the function of each part. The functional model is then compared to the knowledge base to determine both which functions have had failures and what level of failure was recorded [12, 13]. RED can be used early in the design process, immediately after a concept has been formed, so risks can be assessed before significant resources have been dedicated to developing a product. The RED method pulls knowledge from a knowledge base instead of an experienced team, so any technical professional who understands the function of his/her intended design can use the method. However, the current version of the RED failure mode taxonomy is insufficient for new chemical products. A broader taxonomy of failures is needed.

Chemical Failure Mode Taxonomy Addendum Methodology

The taxonomy for elecro-mechanical systems was developed to provide a common classification of failure modes that would improve risk communication [33].

Tumer et al. (2003) identified 51 failure modes. These failure modes were described using the physical process that caused the failure, using a physics-based description [33]. This approach was used both to be consistent and to provide future users, such as designers, with an accurate description of the nature of the failure. This research moved towards standardizing a failure mode taxonomy. The work paved the way to a standardized failure mode taxonomy, automatic risk identification, and assessment of electro-mechanical products using the RED analysis method [12, 13]. In turn, the failure mode taxonomy was then broadened into chemical failure modes to extend the RED methodology into the chemical industry [34]. Ombete (2009) added four chemical failure modes to the taxonomy: catalytic effect, charge imbalance, diffusion, and free radical formation. Both reviewing these failure modes with industry experts and examining semiconductor failures are the first steps in enabling the semiconductor industry to benefit from the recent advances in risk communication, identification, and assessment.

To broaden the taxonomy, 33 research papers were analyzed for chemical failures of the lithography process. These papers focused on the chemical research into the lithography process in the semiconductor industry, and were published through the *international society for optics and photonics* (SPIE), *The Electrochemical Society* (ECS), the *Journal of Micromechanics and Microengineering*, proceedings of the *International Conference on Semiconductor Technology*, the *Materials Research Society* symposium proceedings, *Journal of Photopolymer Science and Technology*, and *Solid State Technology*. Research into the chemical failures of the lithography process allows for the broadening of the failure taxonomy with a focus on a well-defined industry process.

Each paper was analyzed for specific mentions of failures that were deviations from the desired function. For example, according to Guerrero (2011, 79720Q-1), “As a consequence of this polarity switch, mismatch of surface energies between layers occurs which can be responsible for line collapse.” A line collapse failure is described and is later shown in a SEM cross section of a line detaching from the surface. This example demonstrates that line collapse was the failure mode, caused by a mismatch of surface energies. Each paper was analyzed and the data was recorded. The results were examined to determine classifications of failure modes in the semiconductor industry.

Chemical Failure Mode Taxonomy Details

The technology used to name the failures was not consistent throughout the 33 papers investigated. Therefore, a grouping process was used to define failure mode representations for the updated descriptions. This research produced 18 failure modes grouped into four primary identifier groups, as shown in Table 1. The failure modes were the physical processes that connected the failure causes to the effects on either the final lithography pattern or the later processes. The groups of these failure modes were each described by a primary identifier, which is a clear and basic description of each group [33]. The failure modes were grouped because some of the modes were either similar or located at the same stage in the lithography process. The following section describes each primary identifier as well as the related failure modes that resulted from this process.

Table 1 Chemical failure mode results

Primary Identifier	Failure Mode	Definition	Source
Gas Release		The release of a gas, when a solid is baked	
	Sublimation	The phase transition directly from a solid to a gas, during baking	Carr, 2010; Brown, 1994
	Outgassing	The release of dissolved or bound gas when a solid is baked	Neef, 2007; Strong, 1938
Feature Failure		The failure of a patterned feature to meet requirements	
	Line Roughness	The edge of the line is rough, and thus has high spatial complexity	Xu, 2009; Cao, 2002
	Critical Dimension Change	The width of the line is higher or lower than the specification defines	Jurajda, 2009; Okoroanyanwu, 2010
	Line collapse	The feature moves from vertical alignment to falling over	Guerrero, 2010 & 2011; Lowes 2010 & 2011
Defects		A foreign object, or disruption in the uniformity and consistency of the film	
	Fall-on particles	A foreign object that falls onto the film	Harumoto, 2009
	Bubbles	A bump in the film caused by a gas pocket	Smith, 2010
	Craters	A depression caused by a burst bubble	Smith, 2010
	Blob	Also called Satellite or Cat-paw, liquid droplets cause by residual developer	Harumoto, 2009
	Bridge	An unwanted connection between two features	Harumoto, 2009
	Printing	An unwanted feature printed from an error or defect in the exposure process	Harumoto, 2009
	Bottom layer	A defect in a layer beneath the top layer	Harumoto, 2009
	Pin holes	A void, or hole in the film	Smith, 2010
	Bumps	A bump in the film caused by and underlying object	Smith, 2010
Interface Failures		A failure at the interface between two coatings	
	Residue	A thin coating, not necessarily uniform, of the top film that remains on the bottom coating after the top film has been removed	Guerrero, 2006; Washburn, 2009; Lowes, 2010
	Scumming	Material remaining between two features, at the bottom of the feature	Neef, 2009; Lowes, 2011
	Footing	A flaring at the bottom of a feature, that juts out like a foot	Guerrero, 2011; Neef, 2008, Guerrero, 2006
	Undercut	A necking at the bottom of a feature that looks like cut has been removed at the base of a feature	Neef, 2007; Guerrero, 2006

Gas Release

The first primary failure mode identifier was gas release. Two similar failure modes were also identified: sublimation and outgassing. These two modes were used synonymously to mean the release of a gas from a coated material during the baking process [35, 36]. Further investigation revealed that sublimation is a phase transition process where a material moves from a solid to a gas without going through the liquid phase [37]. Outgassing is separate from sublimation, as outgassing is a release of a trapped gas [38]. Outgassing was determined to be a failure mode because, in one case, it linked the cause of an incorrect catalyst [35] to the effect of a deposition of contamination on the hotplate lid. In the second example, the cause of outgassing was that the chromophore was not completely attached to the polymer [36]. This second example of outgassing again led to deposition of the chromophore on the hotplate lid. This hotplate is part of the processing equipment. If it becomes contaminated, the equipment becomes contaminated and must be either cleaned or replaced to maintain the integrity of the manufacturing process. In extreme cases, the contamination can detach and cause defects [36].

Feature Failure

The primary identifier of feature failures contained line roughness, critical dimension (CD) change, and line collapse as failure modes. Both a line and its corresponding space are two of the fundamental features used to make ICs; two additional features are contact holes and pillars [3]. Causes that lead to failures from line roughness, CD change, or line collapse will then lead to either poor electrical effects or a loss of the pattern. As an example, acid from a photo-acid generator (PAG) in the underlayer diffused, causing line roughness [39]. This line roughness then affected the performance of the device [40]. Critical dimension change had different causes, but had the same effect as line roughness [41]. Complete loss of a line due to collapse was found to be a very common failure mode with eight separate examples [42, 43, 44, 45, 46, 47, 48, 49]. The causes varied, and the effect was consistent with the feature falling over, as shown in Figure 2.

Diffusion was a cause of line roughness, and possibly footing, residue and scumming. These failure modes are discussed in the following sections, and have a common connection with PAG and acid. Ombete, (2009) identified diffusion as a failure mode. Diffusion was consistently found to be a cause, not a failure mode, in the research performed in this study. For example, following the [cause → failure mode → effect] logic, diffusion caused the acid to move into the line, increasing the roughness. This roughness then affected the device performance [39, 40]. Additionally, diffusion was found to be integral to how chemically amplified photoresists perform [5, 3]. The connection between diffusion and photoresist performance indicates that diffusion can be beneficial. Therefore, this research points to diffusion as a cause of failure, not a failure mode.

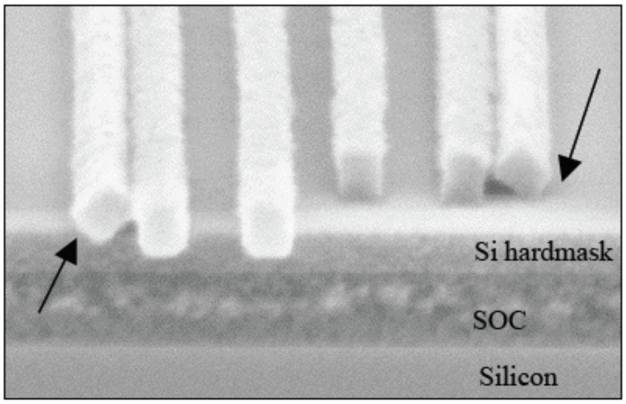

Fig 2 Line collapse example

Photos used by permission of Brewer Science, Inc. (Source: Guerrero et al., 2011)

Defects

The third primary identifier group was named defects, and contained several different failure modes [35, 50, 51, 3, 52]. Bubbles, craters, pinholes, and bumps are types of defects [51]. A defect is defined as a foreign object, disruption in the uniformity, and consistency in the coating. These defects affect the device by causing either shorts or opens in the circuit in later processing steps [51]. In addition to bubbles, bumps and craters, defects such as fall-on particles, bridge, printing, and bottom layer defects were also found [52]. An example of several defects is given in Figure 3.

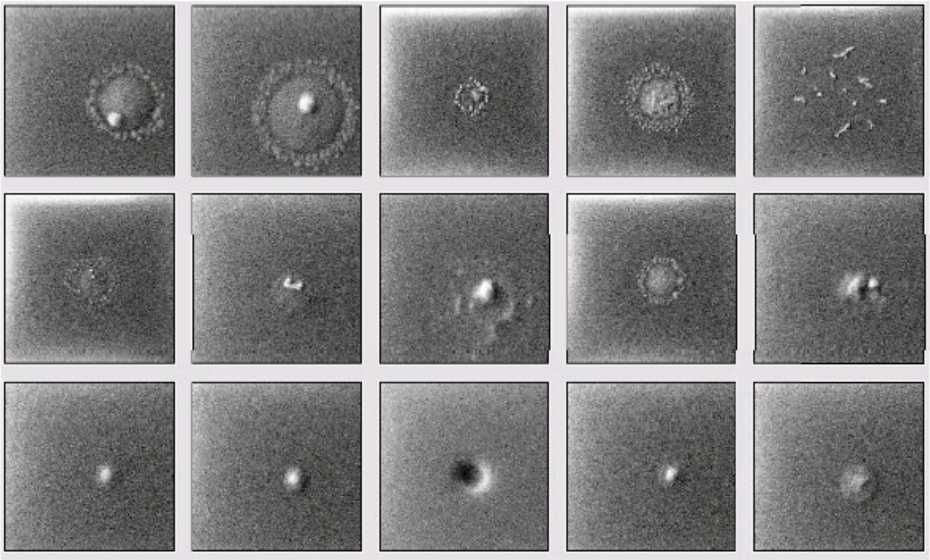

Fig 3 Defect examples

Photos used by permission of Brewer Science, Inc. (Source: Smith et al., 2010)

Interface Failures

The last primary identifier was interface failures. Interface failures are defined as a failure at the interface between two layers and are usually between two lines. 14 examples were found during the literature review [42, 43, 44, 53, 54, 41, 39, 55, 45, 56, 47, 57, 58, 59]. This group of interface failures consisted of residue, scumming, footing, and undercut failures. Residue was defined as a film remaining after the development step. This film is typically very thin and difficult to measure [59, 54, 47]. Residue is caused by improper processing such as, baking at either too high of a temperature [59, 54], using the wrong components, or by selecting an incorrect component ratio, such as too much PAG [47] or by the choice of the substrate [54]. The effect of residue is a limited process window, or pattern transfer errors [59, 54].

Scumming is another failure mode. Like residue, scumming, is usually between two lines. Scumming was driven by improper processing conditions and components were to blame, such as lack of acid [43]. Scumming was also caused by intermixing of the two layers [60]. Figure 4 shows an example of scumming, which is the material remaining between the features. Because scumming exists, the pattern is incomplete and cannot be transferred. The pattern transfer process is thus affected.

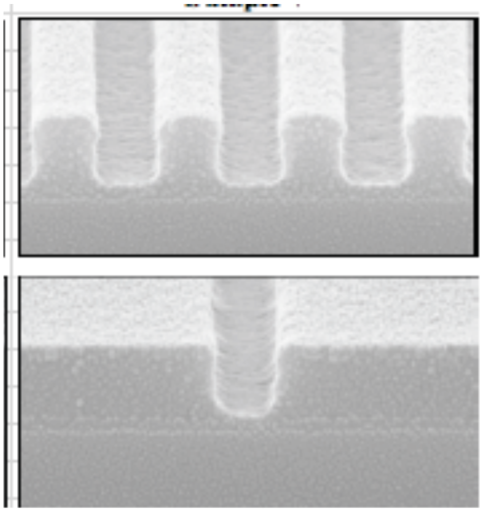

Fig 4 Scumming example

Photos used by permission of Brewer Science, Inc. (Source: Lowes et al., 2011)

Footing is a slight flare at the interface between the photoresist pattern and the layer underneath. The flare looks like a small foot sticking out at the base of the feature, as shown in Figure 5. Footing had several different causes, such as too little diffusion [42], wrong BARC thickness [44, 41, 57, 58], incompatibility of the two layers [53], improper absorbance of the BARC [41], improper acid loading was off [39], incorrect bake temperature [45], misaligned activation energy of the BARC and photoresist [47] and intermixing of the layers [60, 59]. Footing is an improper pattern that will not transfer correctly, causing device failure.

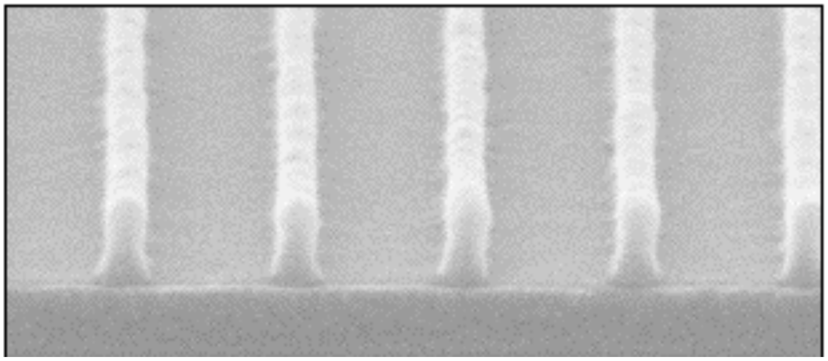

Fig 5 Footing example

Photo used by permission of Brewer Science, Inc. (Source: Guerrero et al., 2009)

An undercut is a decrease in the critical dimension at the base of a feature. When looked at through a cross section (see Figure 6), an undercut appears to be either a necking of an indentation. This failure mode is caused by thermal energy deviations, such as a bake temperature that is too low, a bake time is too short, or, conversely, the combination of a high bake temperature and a short bake time [55]. A low bake temperature is also the source of undercut [36, 59]. Much like footing, the undercut of a line is an incomplete pattern that does not transfer correctly and will cause device failure.

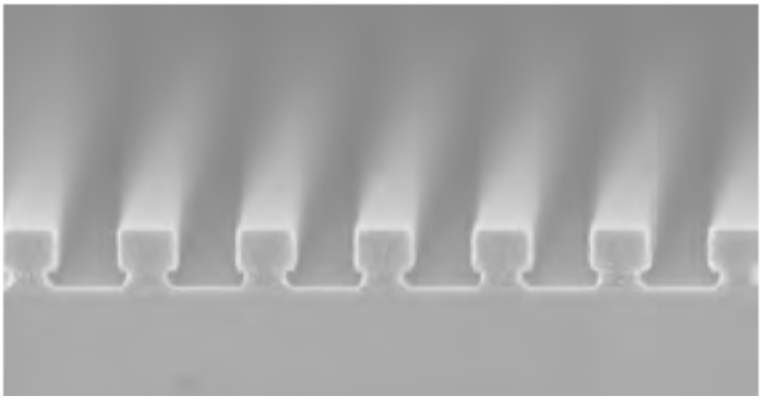

Fig 6 Undercut example

Photo used by permission of Brewer Science, Inc. (Source: Neef & Thomas 2007)

Case Study

An industrial research paper providing information on a chemical failure was examined to validate the taxonomy. This paper was not used for the development of the taxonomy. The paper was reviewed for specific mentions of failures, which were deviations from the intended functions. The selected paper reported an advanced double patterning lithography process used in the semiconductor industry [61]. Bae (2009) in particular reported on a double patterning process that involved printing a pattern, then using a process to stabilize that pattern so that subsequent processing, including additional patterning, could be performed on top of the first pattern, and not affect the first pattern. If the pattern changes during the curing process, then the desired function of a stable pattern is not reached and the pattern is considered a failure.

The double patterning process introduced a new curing agent after the first lithography step. The curing process involved both thermal and chemical approaches, with the goal of locking the first pattern so the second pattern could be applied. Understanding this, Bae (2009) discussed two chemical failure modes: CD change and line edge roughness. The CD change was caused by both the chemical and the thermal curing processes. The CD change failure came from both a growth of the CD and a shrinking of the CD. The CD change in Bae's study, was caused by the curing agent. The CD change in Jurajda, 2009, one of the sources used above to identify CD change as a chemical failure mode, was caused by a BARC thickness change.

Line edge roughness was the second failure mode covered by Bae. This failure mode is caused by acid diffusion. During the chemical process, acid can diffuse into the line so that the roughness of the line increases through processing [61]. Line edge roughness was also identified in the chemical failure mode taxonomy above. The cause of line edge roughness from Xu, 2009 was also acid diffusion.

For the chemical failure modes identified in Bae's study, CD change and line edge roughness were both covered in the chemical failure mode taxonomy above. This case study shows by example that the chemical failure mode taxonomy assembled in the paper accurately represents common failure modes found in the semiconductor materials industry.

Summary

This research fortified the failure mode taxonomy by including chemical failures from the lithography process in the semiconductor industry. Eighteen separate failure modes were identified and grouped into four primary identifiers. Definitions of each failure mode were obtained from a documented source following the physical description method previously published. Each was then described, and pictures for all of the failure modes were supplied for reference. Except for residue, which had not been captured with a picture.

The chemical failure mode taxonomy that was generated was then tested using a case study. The analysis of the case study resulted in its failure modes matching two of those in the new taxonomy. These case study results indicated that the method is robust and the chemical failure mode taxonomy is thorough.

Thus, this research will enable a risk analysis in high technology based products. This analysis can help both engineers and designers examine their products using historical failure data. The taxonomy is a living database that grows with time, adding increased value as more high quality information is added to it. Further work is needed to support the growth of the taxonomy in chemical failures and other technical areas.

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II. Chemical Risk in Early Design (C-RED)

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Abstract

The purpose of this paper is to present a methodology to identify risks in the chemical product development process. This work will enable comprehensive risk analysis in products that have a chemical based subsystem, such as those used in the lithography process in the semiconductor industry. Previous work has broadened the failure mode taxonomy used to aid risk identification in electromechanical products to include chemical failures from the semiconductor industry. The current work focuses on leveraging the broadened failure mode taxonomy and historical failure cases to automatically generate potential risks of chemical based products.

1 Introduction

The purpose of this paper is to present a methodology to identify risks in the chemical product development process. Chemicals become materials and parts that combine to create value for the end user, and in many cases the product value comes from the basic material design. For example, a capacitor is a simple electronic component that consists of parallel plates with a dielectric[1]. The plate and dielectric design determine the electrical characteristics of a capacitor, and if one of the plates is an electrolyte, then the capacitor is called an electrolytic capacitor. Thus the design of the electrolyte material becomes critical to the capacitor performance. Aluminum electrolytic capacitors are used in consumer electronics to smooth out the flow of electricity and in 2003 the ABIT Computer Corporation used Aluminum electrolytic capacitors containing an electrolyte that was missing key chemical additives in its formulation[2]. The missing additive made the electrolyte chemically unstable when charged, and caused the electrolyte to generate hydrogen gas, resulting in reports of the electrolyte leaking out of the capacitor and exploding capacitors[2]. Lien Yan, the company who manufactured the electrolyte saw a 30% drop in orders as a result of the failures[2]. The design of the electrolyte was incorrect, causing the material to fail, which led to capacitor failure and thus the motherboard to stop working, which in turn shut the computer down. Such a small part of the overall system, lack of the proper additives in an electrolyte, was enough to cause the whole system to fail.

Chemicals permeate everyday life, from the dyes in textiles to the materials in the photolithography process, used to make semiconductor devices, often called chips. The fundamental process that both enables and limits semiconductor device fabrication is the photolithography process. This paper focuses on identifying chemical risks in the photolithography process used in the semiconductor industry. Photolithography involves reducing, then transferring a pattern precisely for several million times over a device generation. Fundamentally, photolithography is a series of chemical reactions interspaced by optical, thermal and physical processes. Figure 1 shows a very basic process flow to create a simple line and space pattern. Polymer films such as bottom anti-reflective coatings (BARC) and photoresists are coated onto the wafer, which is then baked. The baking process either crosslinks or cures the films to stabilize them. The wafer is transferred to an exposure tool and the pattern is transferred through the optics to the polymer films on the substrate, causing a photochemical reaction. The substrate is then transferred and baked; causing a chemical amplification of the photochemical reaction, which creates and diffuses acid. Then a basic developer is coated over the wafer, causing an acid-base reaction that resolves the exposed pattern. The wafer is rinsed with water to clean it and further processing, including additional chemical reactions, are used to complete the device. Photolithography, in essence, is a series of chemical interactions and reactions that combine to form a pattern on the wafer.

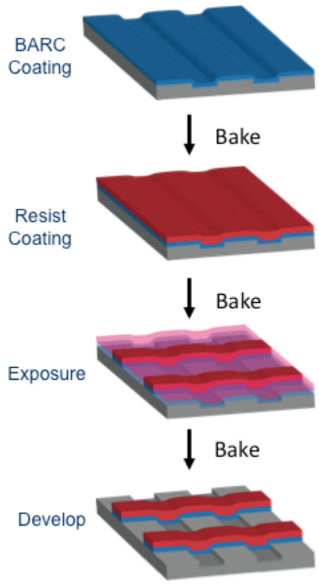


Figure 1: Photolithography process

Graphic used by permission of Brewer Science, Inc.

Chemists, engineers and lithographers who deal with risks associated with photolithography chemicals in the photolithography process will be better prepared and will have a more cost effective method of managing risks. The Chemical Risk in Early Design (C-RED) method uses chemical research information that documented chemical failures, cataloged them and used that structured information to recommend possible risks that researchers and engineers need to consider. C-RED followed the method developed by Granthan-Lough, which was based on identifying and determining risks in electro-mechanical designs, by connecting historical product failures to a product's function[3].

2 Background

2.1 Recent Material Failures

Along with chemical design, the material selection early in the design process can be a source of failure, such as the packaging used in connecting graphics chips to a computer system. Micron scale wires have been traditionally used to make the electrical connections between the chip and the solder balls on the larger package[4]. The more recent method is to place tiny bumps of solder on the chip's active surface, then flip the chip over to connect to the larger device[4]. A cross section view of a wire bond and flip chip is shown in Figure 2. The overall package of a flip-chip is smaller and has better electrical performance than a wire-bond package, however manual replacement of a flip-chip is not an option and thermal management and thermal effects are more challenging in a clip-chip design, requiring careful material design[4,5]. In the flip chip package the small solder bumps that connect the device chip to the substrate must transmit electricity, manage thermal energy and provide mechanical stability. To help with this, an underfill is used to provide support and minimize solder fatigue on the flip chip[4,5]. Through 2007 and 2008 Nvidia produced graphic flip chips with improperly designed solder bumps and underfills[5,6]. The solder chosen was a brittle high lead material with poor adhesion to the eutectic pads it was mated to, combined with an underfill material that became soft (low Tg) at a low temperature of 90°C[5]. As the graphics chip was thermally stressed, this caused the underfill to soften and then the brittle solder bumps broke from their bonds[5]. With the graphics chips disconnected, the computer screen went permanently black for consumers[5,6]. This chip failure forced Nvidia to take a $196 million reserve to cover repair and replacement costs[7], followed by Nvidia loosing 3 billion in market value, resulting in a securities fraud lawsuit[6]. Sources speculated that the poor choice of solder and underfill occurred very early in the design process, and due to the complex design and testing required to verify devices, it made the problem difficult to solve once consumers discovered it[5].

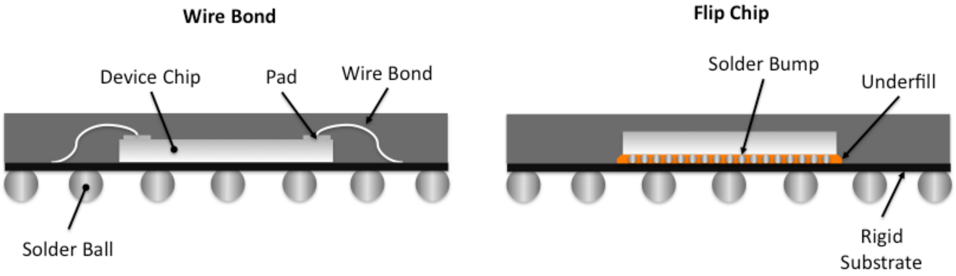


Figure 2: Comparison of wire bonding and flip chip

The decisions the Nvidia engineers made when selecting materials for the solder and underfill incorporated a high level of risk[5]. The risky material decision led to negative consequences for the consumer. Risk is defined as the chance that an undesirable event can occur and the consequences of all its possible outcomes [8,9]. If the risk is not identified and mitigated, the failure of a semiconductor device can result in an enormous cost, similar to the capacitor and very close to the graphics chip example. A dramatic example of a semiconductor industry failure was Intel's recent issue with the Sandy Bridge graphics processor chip. The chip suffered a failure due to a gate oxide that was too thin, resulting in current leaking[10]. The gate oxide separates the gate terminal from the source and drain in a transistor and serves as a dielectric as shown in Figure 3. A voltage is applied to the gate, allowing electrons to flow from the source to the drain through a channel between the two and under the gate. If the gate oxide is too thin, electrons can channel through the oxide to the gate causing current to leak through the device, causing electrical failure of the transistor. Roughly 8 million chips shipped from Intel with too thin of a gate oxide in 2001, this failure cost Intel $300 million in lost sales and $700 million in repairs[10]. This example emphasized how a failure can progress through the semiconductor design process, consuming resources until it is identified.

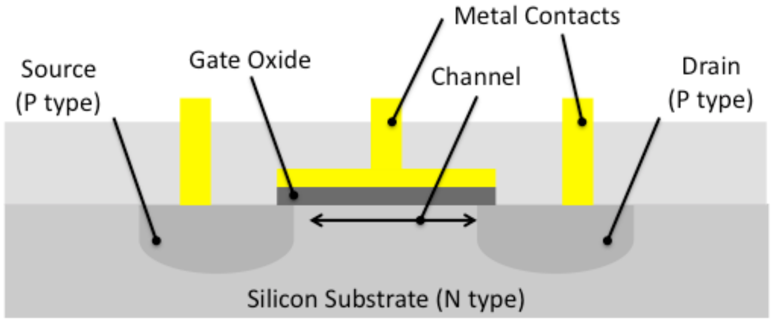


Figure 3: Semiconductor transistor design

The chemical industry uses several risk assessment methods. Several of these methods focus on chemical manufacturing processes since they are connected to the Occupational Safety and Health Administration (OSHA) PSM standard Title 29 CFR 1910.119. This federal regulation requires chemical plants to conduct process hazards analysis (PHA)[11]. PHAs are methodologies that follow systematic approaches to find both hazards and deviations, and are defined by OSHA as a systematic effort designed to identify the significance of hazards associated with either the processing or handling of highly hazardous materials[11]. Along with OSHA, many other entities have PHA guidance. These entities are detailed in government regulations such as 21 CFR 120.7, 29 CFR 1910.119, 40 CFR 68, FAA-DI-SAFT-101, DOT-FTA-MA-26-5005-00-01 and DOE Order 5480.30.

In this work, focus was placed on PHAs documented either under OSHA regulations or had documented use within the industry so that a pattern of legitimate use could be established. The PHAs examined in this study were taken from the code of federal regulations published by OSHA, and included fault tree analysis (FTA), hazard and operability study (HazOp) and failure mode and effects analysis (FMEA). These methods are listed by OSHA as tools that can be used in industry to assist in both determining and understanding hazards and potential failure modes in a chemical process[11]. Fault tree analysis is a quantitative method that uses binary logic to understand how a failure propagation occurs[12,13]. A hazard and operability study, or a hazard and operability review, targets chemical production processes; these studies are semi-quantitative[14,15]. FMEA is a quantitative method designed for products with several parts, such as automobiles[16]. FMEA in particular is very common in the semiconductor industry because semiconductor devices are used in automobiles, and for many years there has been a drive to follow standards connected to the automotive industry, including FMEA recommendations[16].

Risk assessment tools with published use in industry were also analyzed. These included event tree analysis, layer of protection analysis, and risk in early design. Event tree analysis (ETA), similar to FTA, is a quantitative method that uses binary logic to understand how failure propagation occurs[12,13]. Layer of protection analysis (LOPA) targets chemical production processes by assessing the protection of the layers used to mitigate risks in the process[14,15].

Risk in early design (RED) is a contemporary risk assessment approach with broad uses across several industries. RED uses quantitative methods to analyze both risks and potential failures connected to the function of the design. RED is the most recent method, and was created to address the intrinsic knowledge requirement most previous methods faced[8]. Each will be reviewed in the following sections.

2.2 OSHA Recommended PHAs

FTA is an analysis technique that starts from a top or initiating event. It looks backwards to what could have caused the top event by determining the connections between the lower level events[17]. An FTA is helpful because it provides an engineer with a simple visual mechanism to see how a series of complex events could connect and cause a failure. FTAs have been incorporated into the chemical industry, focusing on chemical plant operations[18,19,20]. An FTA, however, would be very difficult to complete before a chemical product is mature, as the multitude of unknown outcomes from the chemical process would need to be determined. Additionally, FTA focuses only on one top event at a time, which means an entire tree must be generated for each top event. This approach becomes very cumbersome when trying to evaluate a complex product that may have multiple failures[21].

HazOp is a commonly used method that helps identify hazards in chemical industries. During HazOp, a knowledgeable team gathers and follows a structured list of guide-words[22]. Through a series of meetings, the team works through the process to evaluate potential issues, their causes, and possible solutions[23]. However, much like a LOPA, HazOp focuses on the chemical production process, and not the early research stage in which the chemical is developed[24,25]. The HazOp process requires a team of experts with specialized knowledge and takes a large amount of time to complete due to its thorough nature[24].

FMEA may be the most well-known risk assessment tool in the semiconductor industry, due to the connection between the semiconductor and the automotive industries following the QS-9000 quality standard. The FMEA process analyzes the intended function of the product and the information is separated into failure effects, modes, and causes[23,26,27]. Both the logical process and the quantitative results have made FMEA a straightforward tool to use when developing products[28]. The value of a FMEA is limited to the intrinsic knowledge of the team and it is typically completed later in the design cycle, after product design and testing knowledge has been acquired.

2.3 Additional Risk Assessment Tools Used In The Chemical Industry

ETA works in the opposite logical direction when compared to FTA. ETA begins with a failure, and then propagates it forward through different binary pathways to a final outcome[29]. The goal of the ETA is to evaluate all the possible outcomes that could come from the initiating event and condense the analysis into a more concise picture[21,29]. This method is advantageous because multiple failures can be analyzed allowing the weakness of the system to be identified[30,31]. However, a very thorough understanding of how something works must first exist so that the parts of an ETA can be built[32]. Much like FTA, ETA only focuses on one initiating event at a time. Focusing on one event at a time would create a very unmanageable approach for a chemical product.

LOPA, as its name implies, is a model that builds separate layers of protection. These different layers serve as barriers to stop the progression of undesirable events[33]. The layers typically start with the chemical process and then progress through internal protections in the chemical plant ending at an emergency response from the community. LOPA is focused on chemical plant operations, helping break down complex processes into simple layers so that protection methods can be viewed and general decisions can be made[34]. LOPA, however, requires an experienced, knowledgeable team focusing on only one cause and one consequence[35]. Though LOPA is used in chemical production, it does not address the research stage when a chemical is being developed. In fact, one reference about LOPA recommended that a better method than building layers of protection is to develop a fundamentally better chemical[33].

2.4 Risk In Early Design

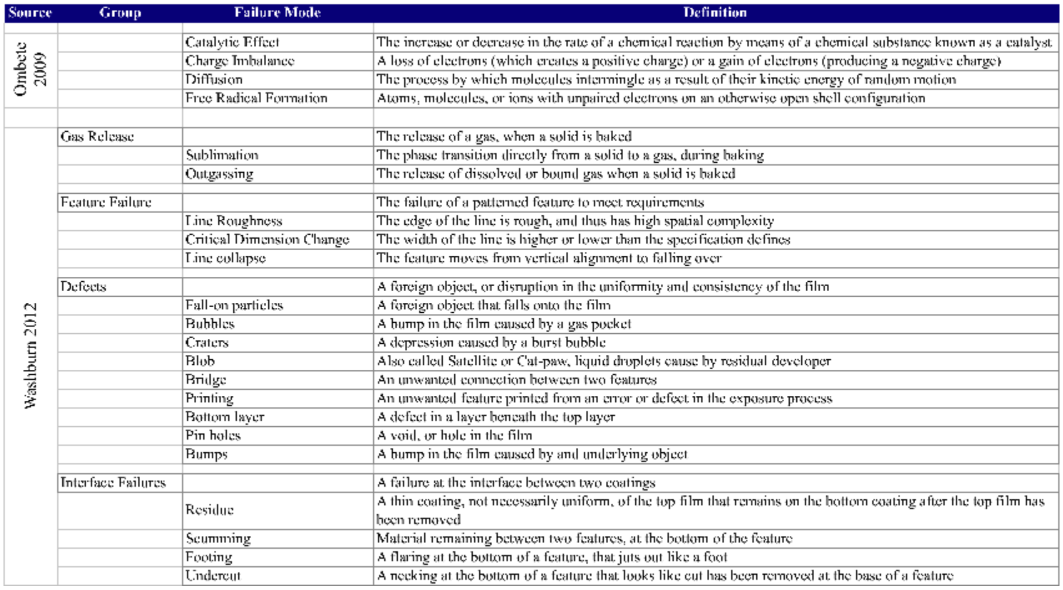
The RED method is targeted at identifying risks early in the design process, before a prototype has been built, when the design is still in the concept stage. RED connects either a product's or a process' basic functions, using a functional model, to a historical database of failures using a standardized failure mode taxonomy[36,37]. This database contains a history of failure modes, their likelihoods, and their consequences. Because the data on product failures comes from historical failures, inexperienced engineers and designers alike can use RED to evaluate their products early in the design phase[36,37]. The use of matrices provides a simple approach that defines both function and failure combinations that are then quantified by the database by both likelihood and consequence, making RED a quantitative approach[36,37]. For RED to generate a robust analysis, the historical database must also be robust. Additionally users must be trained to build functional models and interface with the software.

One of the differences of RED compared to the PRAs descried above such as ETA, FTA, LOPA and HazOp, is that RED can be used early in the design cycle when only a product's concept exits. A strength of RED compared to HazOp and FMEA is that RED does not require a team with extensive knowledge and experience to develop a valuable result. The RED method pulls information from a knowledge base instead of an experienced team, so any technical professional who understand the function of the intended design can use the method. RED connects a product's or process's basic functions, using a functional model, to a historical database of failures using a failure taxonomy[36,37]. This mapping is accomplished by developing a functional model, which is a series of basic functions that are used as a common interface between the product and the database, using the taxonomy. The database contains a history of failure modes, their likelihoods and consequences.

A taxonomy establishes a consistent resource to future users by providing an accurate and straightforward description of the nature of the failure. The taxonomy for chemical products was started by Ombete in 2009 and is shown in the top of Table 1[38]. Washburn broadened this taxonomy in 2012, which is shown in the lower half of Table 1[39]. The failure modes were described using the physical processes that the research showed caused the failure.

Once the groundwork of the taxonomy is laid and the functional model of the product or process is built, the correct functions can be selected, and the rest of the RED process can be applied. The RED process uses a matrix approach to map the collected function's potential failures, likelihood and consequences. The function-component matrix (EC) consists of the product's functions and the individual components of the product. The component-failure matrix (CF) is composed of the

Table 1: Chemical failure mode taxonomy[38,39]



Source	Group	Failure Mode	Definition
Ombete 2009		Catalytic Effect	The increase or decrease in the rate of a chemical reaction by means of a chemical substance known as a catalyst
		Charge Imbalance	A loss of electrons (which creates a positive charge) or a gain of electrons (producing a negative charge)
		Diffusion	The process by which molecules intermingle as a result of their kinetic energy of random motion
		Free Radical Formation	Atoms, molecules, or ions with unpaired electrons on an otherwise open shell configuration
Washburn 2012	Gas Release		The release of a gas, when a solid is baked
		Sublimation	The phase transition directly from a solid to a gas, during baking
		Outgassing	The release of dissolved or bound gas when a solid is baked
	Feature Failure		The failure of a patterned feature to meet requirements
		Line Roughness	The edge of the line is rough, and thus has high spatial complexity
		Critical Dimension Change	The width of the line is higher or lower than the specification defines
		Line collapse	The feature moves from vertical alignment to falling over
	Defects		A foreign object, or disruption in the uniformity and consistency of the film
		Fall-on particles	A foreign object that falls onto the film
		Bubbles	A bump in the film caused by a gas pocket
		Craters	A depression caused by a burst bubble
		Blob	Also called Satellite or Cat-paw, liquid droplets cause by residual developer
		Bridge	An unwanted connection between two features
		Printing	An unwanted feature printed from an error or defect in the exposure process
		Bottom layer	A defect in a layer beneath the top layer
		Pin holes	A void, or hole in the film
		Bumps	A bump in the film caused by and underlying object
	Interface Failures		A failure at the interface between two coatings
		Residue	A thin coating, not necessarily uniform, of the top film that remains on the bottom coating after the top film has been removed
		Scumming	Material remaining between two features, at the bottom of the feature
		Footing	A flaring at the bottom of a feature, that juts out like a foot
		Undercut	A necking at the bottom of a feature that looks like cut has been removed at the base of a feature

product's components and the potential failure modes. These two matrices are multiplied to produce the function-failure matrix (EF), as shown in equation (1).

$$\mathbf{EC\ x\ CF = EF} \qquad \mathbf{(1)}$$

To help categorize the history of failures in the database, basic heuristics were produced to guide the user in selecting the correct mapping combinations[36,37]. The selection is based on how the product is used, and where it is in an overall system. The description below details each heuristic, and Table 2 provides a view of where each heuristic resides[36,37].

System Level:	During this stage of design the product as a whole is considered, and the question is asked, "Is this a risky product?"
Subsystem Level:	During this stage of design the pieces and subsystems of a product are considered, and the question is asked, "Which part has the most risk?"
Human Centric:	A human centric product is one in which a human is central to its operation.

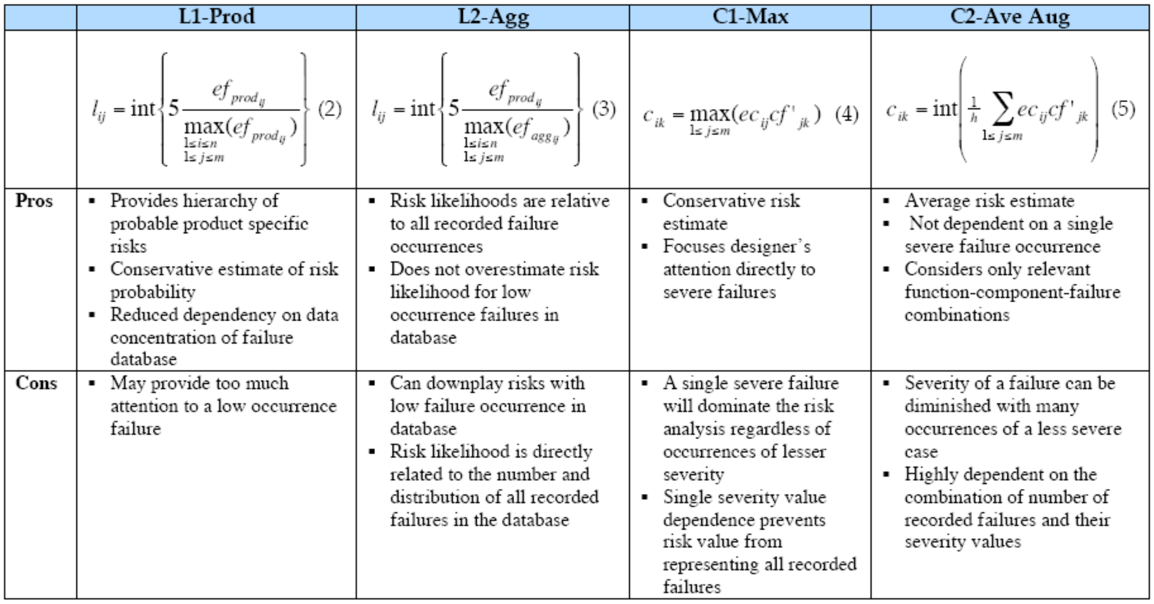
Unmanned: An unmanned product is one that does not directly interact with a human during its intended operation.

Table 2: RED heuristics[36,37]

		Product Type	
		Human Centric	Unmanned
Design Level	System Level	L2, C1	L2, C2
	Subsystem Level	L1, C1	L1, C2

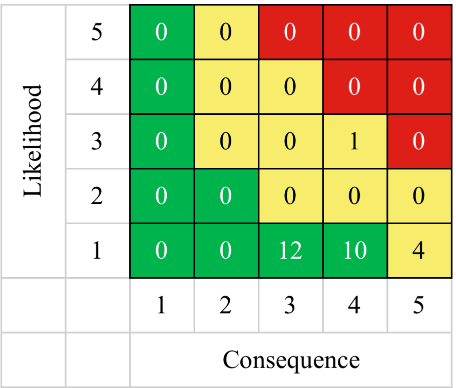
The consequence and likelihood calculations are shown in Table 3. The L1 likelihood calculation focuses on subsystem designs, where L2 is targeted at the system level. The C1 consequence calculation is a human centric product and C2 is an unmanned system[36,37].

Table 3: RED heuristics[36,37]



	L1-Prod	L2-Agg	C1-Max	C2-Ave Aug
	$l_{ij} = \text{int}\left\{5\frac{ef_{prod_{ij}}}{\max\limits_{\substack{1\le i\le n\\ 1\le j\le m}}(ef_{prod_{ij}})}\right\}$ (2)	$l_{ij} = \text{int}\left\{5\frac{ef_{prod_{ij}}}{\max\limits_{\substack{1\le i\le n\\ 1\le j\le m}}(ef_{agg_{ij}})}\right\}$ (3)	$c_{ik} = \max\limits_{1\le j\le m}(ec_{ij}cf'_{jk})$ (4)	$c_{ik} = \text{int}\left(\frac{1}{h}\sum\limits_{1\le j\le m} ec_{ij}cf'_{jk}\right)$ (5)
Pros	▪ Provides hierarchy of probable product specific risks ▪ Conservative estimate of risk probability ▪ Reduced dependency on data concentration of failure database	▪ Risk likelihoods are relative to all recorded failure occurrences ▪ Does not overestimate risk likelihood for low occurrence failures in database	▪ Conservative risk estimate ▪ Focuses designer's attention directly to severe failures	▪ Average risk estimate ▪ Not dependent on a single severe failure occurrence ▪ Considers only relevant function-component-failure combinations
Cons	▪ May provide too much attention to a low occurrence failure	▪ Can downplay risks with low failure occurrence in database ▪ Risk likelihood is directly related to the number and distribution of all recorded failures in the database	▪ A single severe failure will dominate the risk analysis regardless of occurrences of lesser severity ▪ Single severity value dependence prevents risk value from representing all recorded failures	▪ Severity of a failure can be diminished with many occurrences of a less severe case ▪ Highly dependent on the combination of number of recorded failures and their severity values

The use of matrices provides a simple approach to define function and failure combinations, which are then quantified by the database, using both likelihood and consequence. The results of the analysis are produced in a fever chart, which serves as a clear and concise way to communicate the results. The color-coding follows a stoplight pattern, with the green meaning low risk, yellow meaning moderate risk and the red meaning high risk, as shown in Figure 4. The numbers in the cells correspond to the likelihood and consequence data from the historical failures in the database[36,37].



Likelihood	5	0	0	0	0	0
	4	0	0	0	0	0
	3	0	0	0	1	0
	2	0	0	0	0	0
	1	0	0	12	10	4
		1	2	3	4	5
		Consequence				

Figure 4: Fever chart example

3 Applying The C-RED Method

The C-RED method requires a series of discrete steps that build on the RED method. These steps guide the user through a structured process, step by step. The RED method uses matrix algebra to combine the functions of the system or sub-system, the components, and failure modes to the frequency and severity of the failures. Though the calculations are the same, the heuristics change. Most chemicals are used as part of a process, or sub-system, that connects to a larger system used to make a final product. So for chemical sub-systems, the focus on severity changes from a person to a process or equipment.

Step 1: The first step is to build a database of historical failures, using a common taxonomy. To do this a large number of failures must be identified that have chemical failure modes or chemical subsystems that were the failure mode. The failure cause, mode and effect must be separated. Then the failure mode is extracted, and recorded following the failure mode taxonomy[38,39].

Step 2: After the failure modes have been identified and recorded, they are ranked. The ranking focuses on how severe the impact is, with a low impact being 1 and a high severity being 5. Table 4 shows how the consumer based severity table was adapted for use with chemicals and chemical processes. The focus of the severity changed from a person to the customer's process or equipment that would be using the chemical or chemical process.

Table 4: Severity table for chemicals and chemical processes

1	2	3	4	5
Minor nuisance to customer	Nuisance to customer, and requires a process change	Causes significant process shift or disruption	Customer process fails	Customer process fails and their equipment or product is contaminated or damaged

Step 3: The matrices are now created using the data from previous steps. The EC matrix documents which functions are connected to list of components. The CF matrix connects the components with the researched failure modes, focusing on how many modes were documented to create the frequency. The CF' is like the CF except that it records severity instead of frequency. The equation (1) is used to create the EF matrix, which creates the failure modes to the functions.

Step 4: Once the groundwork is completed, a functional model is built that describes the process that will be analyzed. The steps are defined for the process, and are then broken down into individual functions that are connected using different energy flows. The functions are structured in a verb and then object connection, such as transport solid.

Step 5: The functions are then extracted from the model and entered into the C-RED database. The database maps the functions to the risk likelihood and consequence. For this analysis and unmanned sub-system mapping was selected, since the processes do not require human interaction and are part of larger process. Equation (2) shows the L1-prod, which is selected for sub-system designs. Equation (3) shows the C2-ave aug which is used for unmanned cases. The calculation results of (2) produce the likelihood that a function will fail from one of the documented failure modes. The results of equations (3) provide the consequence of the failure mode.

$$l_{ij} = \operatorname{int}\left\{ 5 \frac{ef_{prod_{ij}}}{\max\limits_{\substack{1<i<n \\ 1<j<m}} (ef_{prod_{ij}})} \right\} \tag{2}$$

$$c_{ik} = \tfrac{1}{h} \sum_{1<j<m} ec_{ij} cf'_{jk} \tag{3}$$

Step 6: Once the calculations are complete, the results must be communicated. The failure modes, likelihoods and consequences are communicated in two ways. A report is produced in the form of a table that lists the data. A fever chart is also produced as shown in Figure 3, which provides a stoplight color-coded grid of consequence and likelihood of the failures.

4 A Case Study

The purpose of the case study was to validate the C-RED method, using the pre-established failure mode taxonomy. Wang 2012 was selected for the case study, and reported on the causes of blob defects, which are defects caused by residual material left behind after the develop process[40]. Wang et. al. developed a solution to the defect problem by altering the chemistry of the layers used in the lithography process, which suited the chemical nature of C-RED very well.

Steps one through three were previously completed[39]. The next step is to build a functional model. So one was built for the case study based on the photolithography process that is used to pattern semiconductor substrates, the last step is the developing the wafer. Figure 5 shows the functional model of the develop process, listing some of the functions in the robot flow and the functions in the wafer flow. Four functions were identified in the develop process; transport solid, coat solid, store fluid and transport fluid.

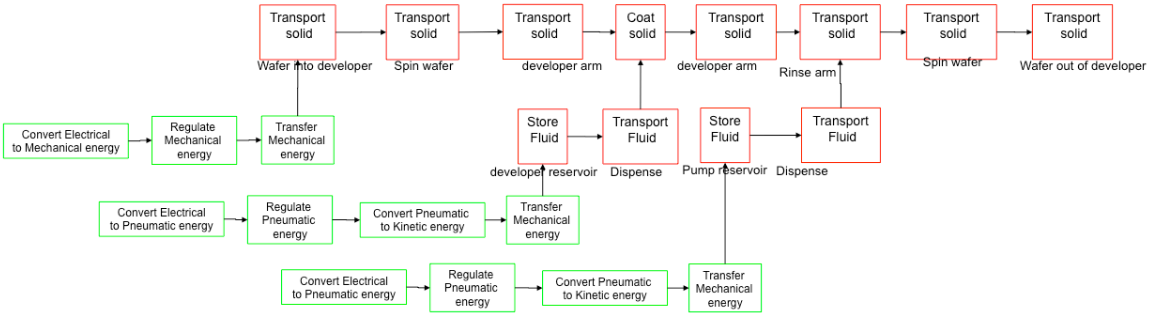


Figure 5: Functional model of the develop process

The goal of the case study was to verify that C-RED would identify failures in an actual case. The case study identified blob defects in the develop step of the lithography process, and blob defect was also in the taxonomy from previous research[39]. If the C-RED method works, blob defect should appear through the analysis. Table 5 shows the results of the C-RED analysis after completing step 5, along with the fever chart in Figure 6. The C-RED analysis did produce blob as a failure mode, connected with the function of transferring a liquid. Blob defects had a low likelihood of occurring at level one, and a medium consequence at level three.

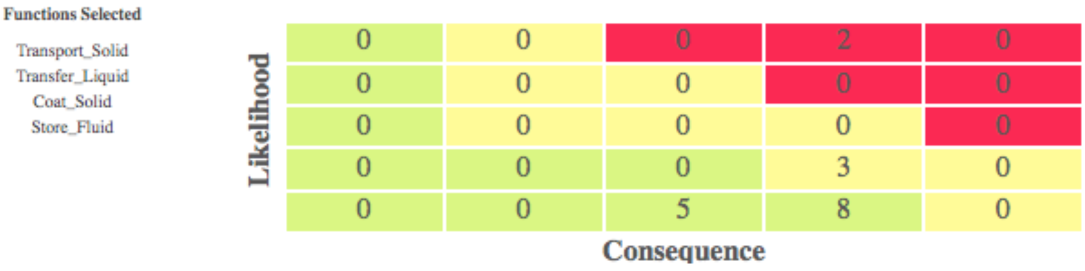
The analysis also produced two failure modes that were fives on the likelihood and four on the consequence scale. Both were line collapse, though from two different functions. Line collapse was not mentioned in Wang 2012, nor was any of the other failure modes. Since Wang 2012 focused on blob defects, other failures may have occurred and were not published. Through an interview with Wang it was learned that the line-collapse, footing and microbridging occur regularly when developing lithography processes he has worked on[41]. However, they were not part of the 2012 study and Wang could not comment on the connection of failures outside of blobs for the materials and processes the case study researched[41].

The C-RED process did identify blob defects. The function of transferring a liquid was also consistent with the research of Wang 2012, "… the blob defects are due to the aggregation of the resist components during alkaline developer development and DI water rinse steps, and the aggregated resist components then fall back onto the wafer surface forming the blobs. This mechanism is also referred to as pH shock or reduced zeta potential of the resist components in the developing/rinsing transition stage."

Wang's research showed that blobs formed during the develop and rinse steps, when liquid developer and liquid water were flowing across the surface of the wafer, and the taxonomy associated blob defects with the transfer of liquid. This connection shows consistency in the research methods and a real world case study, and demonstrates that the taxonomy and C-RED method was verified as effective in identifying failure modes.

Table 5: C-RED report for case study

Severity	Function	Failure Mode	Likelihood	Consequence
High	Store_Fluid	Line_Collapse	5	4
High	Coat_Solid	Line_Collapse	5	4
Med	Coat_Solid	Residue	2	4
Med	Coat_Solid	Footing	2	4
Med	Store_Fluid	Footing	2	4
Low	Store_Fluid	Outgassing	1	3
Low	Coat_Solid	Outgassing	1	3
Low	Transfer_Liquid	**Blob**	1	3
Low	Store_Fluid	Undercut	1	3
Low	Coat_Solid	Undercut	1	3
Low	Store_Fluid	Scumming	1	4
Low	Store_Fluid	Line_Roughness	1	4
Low	Store_Fluid	Critical_Dimension_Change	1	4
Low	Transfer_Liquid	Residue	1	4
Low	Coat_Solid	Critical_Dimension_Change	1	4
Low	Store_Fluid	Residue	1	4
Low	Coat_Solid	Line_Roughness	1	4
Low	Coat_Solid	Scumming	1	4



Functions Selected

Transport_Solid
Transfer_Liquid
Coat_Solid
Store_Fluid

0	0	0	2	0
0	0	0	0	0
0	0	0	0	0
0	0	0	3	0
0	0	5	8	0

Figure 6: Fever chart for case study

5 Summary

The goal of this paper was to present a methodology to identify risks in the chemical product development process. The purpose was to enable comprehensive risk analysis in technology based products. Products that have a chemical based subsystem, such as those used in the lithography process in the semiconductor industry were the specific focus.

A review of the current risk analysis methods showed that there is a need for a tool early in the chemical design process to understand and mitigate risk. Past work in taxonomy research was used as a basis. A case study was then selected, and analyzed[40]. A functional model was built to show the develop process that Wang, 2012 referenced. The functions were then run through the C-RED analysis software, and the results analyzed. The blob defect discussed in Wang 2012 was produced by the C-RED software, along with additional failure modes, verifying the effectiveness of both the taxonomy and the C-RED process.

Thus, this research has produced a risk analysis in high technology based products. This analysis can help both engineers and designers examine their products using historical failure data. The taxonomy is a living database that grows with time, adding increased value as more high quality information is added to it. Further work is needed to support the growth of the taxonomy in chemical failures and other technical areas.

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SECTION

2. CONCLUSIONS

The goal of this research was to both fortify the failure mode taxonomy and to also include chemical failures and then verify that and to present a methodology to identify risks in the chemical product development process. The first paper researched and presented a taxonomy for chemical based systems. The second paper presented the C-RED methodology, including a case study, demonstrating the process.

The value of the C-RED methodology is directly connected to how broad the failure mode taxonomy is. Further research is needed to broaden the taxonomy. Further work could also focus on proving depth to the taxonomy by recording the cause of the failures. The cause may be more valuable to chemical designers, as they are able to chemical the chemical formula and process to adjust for known causes. This is because it is more difficult to adjust a chemical or chemical process to mitigate a failure mode, than it is to prevent it in the first place.

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