Systems Engineering and Modeling at Start-Up Company

Gerrit Muller
Buskerud University College
gerrit.muller@gmail.com

Abstract. Systems Engineering originated in the military and aerospace industry. Typical companies applying Systems Engineering are large, running programs of hundreds to tens of thousands person years. We have been assisting in applying Systems Engineering techniques and methods in a small (tens of persons) start-up company in the semiconductor process and equipment market.

We report our observations in this start-up company with an innovative product operating in a dynamic environment. Start-up companies in general explore new applications or new technologies: an environment full of unknowns, uncertainties and other surprises. In the specific case of semiconductor process and equipment the system is highly multi-disciplinary, amongst others: high precision mechanical, control, optics, chemical, signal processing, and power electronics.

One of the main challenges in a system were so many technologies have to be developed is to create an understanding of the integral system, while working on its components. Every component in itself requires lots of engineering attention, which makes it difficult to pay sufficient attention to the system itself.

We applied the recommendations from the Systems modeling and Analysis course taught at Buskerud University College (BUC), such as time-boxing, multi-view iteration, visualization, and quantification. The combined effect of these recommendations has been that the engineering of the components got early system level validation through design reviews. A number of significant risks were identified during the reviews and addressed afterwards.

Introduction

The main purpose of this paper is to describe a case of the application of Systems Engineering techniques and methods at a start-up company. We have argued before [Muller 2009] that Systems Engineering is a rather young field. The field of Systems Engineering needs observational research to facilitate the academic researchers to gradually build up ontologies, followed by theories. This paper provides one more sample of Systems Engineering as it is practiced in the field today.

We specifically apply modeling and analysis techniques as we are teaching these techniques at BUC. The specific contribution of this paper is the application of these techniques in a small start-up company. Systems Engineering originated in the military and aerospace industry. Typical companies in the military and aerospace industry are large, running programs of hundreds to tens of thousands person years. A lot of knowledge captured in the INCOSE Systems Engineering handbook [INCOSE 2007], and standards such as [DoD 2003] originate in these domains. In contrast, this start-up company deploys tens of persons. Note also that the circumstances in the mature and heavily regulated defense industry are quite different than the semiconductor start-up company, where an innovative technology has to penetrate a fast moving industry.

We have been asked by the start-up company to participate as researcher, since the management of the company is convinced of the value of systems engineering for this kind of multi-disciplinary systems. The expectation of the company is that independent researchers are valuable as reviewer and reflector.

The Start-up Company background

Replisaurus Technologies is a Swedish start-up company developing a process to print copper patterns on wafers. We provide here a brief background, based on the website www.replisaurus.com. The founder of Replisaurus developed the technology during his MSc work in California, see [Fredenberg 2005, Möller 2005]. The process replaces 6 process steps in the "back-end" processing facilities by one single step. The process also shows very good printing capabilities: structures in the order of microns with well-defined and sharp walls. In semiconductor design these copper structures have many applications, for example antenna structures for telecommunication chips.

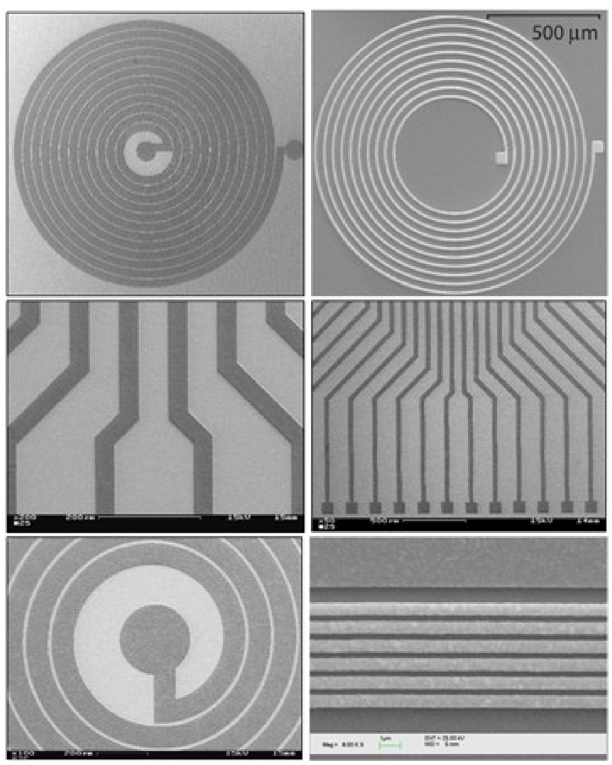

Figure 1. Example of copper structures printed with Replisaurus technology

Replisaurus innovates the copper printing process. Conventional processes require 8 steps to print the copper. The Replisaurus technology, *Electro Chemical Pattern Replication* (ECPR), replaces 6 out of 8 steps by one new step. Figure 2 shows the traditional and the new process.

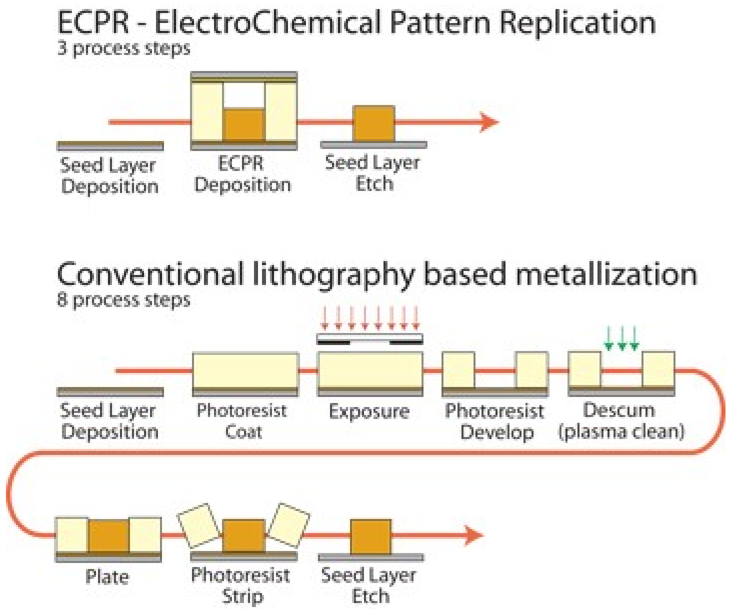

Figure 2. Replisaurus ECPR technology replaces 6 process steps by one process step.

Modeling the System

In 2007 the copper printing process was being developed by means of an improvised printer using prototype modules. Regular copper print equipment, reliable and with high throughput, is needed to facilitate mass production in semiconductor factories (the term semiconductor factories is shortened to fab in the domain). The development of an alpha tool was started in 2007. This alpha tool development focused on the core functions. In 2008 a time-boxed modeling workshop took place, to ensure that the ongoing developments fit well together and fit in the customer context.

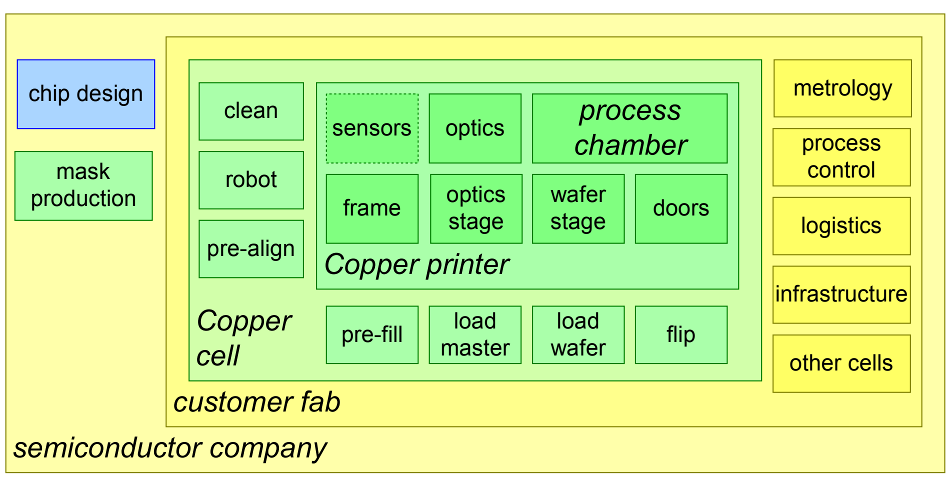

Figure 3. Overview of the different scopes that are relevant for Replisaurus. The *process chamber* contains the core technology required for the copper printing process. The process chamber is part of the Copper printer

One of the outcomes of the modeling is the recognition of multiple hierarchical layers of models. The *cell* is perceived as a single system at semiconductor factory level. Every cell performs one process step on a batch of wafers. The core of the cell is the process chamber. The process chamber is part of a "copper printer" that holds the wafer and the mask-wafer, positions and aligns wafers, applies a contact force during the actual print process. In this paper we will focus on the copper printer in the context of the cell and the factory and as part of the total copper print process.
The core technology of Replisaurus is the copper print process and the related master electrodes (print templates). Replisaurus needed an industry infrastructure including copper printing cells to make a business out of the process itself. The alpha tool will be a complete cell. The development of the copper printer is based on another existing semiconductor system that somewhat approximated the desired functions of the copper printer. Replisaurus bought a small French company that developed the original system that was used in the prototype. The French company is chartered with the development of the copper printer, excluding the process chamber that is being developed by the Swedish development team.

Modeling the Context

The time boxed 2008 workshop had as main goals:

- to make the engineering team aware of the broader context
- to align the design specifications across components

The approach of the workshop was to do a scan of design, specification, and context, followed by an elaboration of the cross cutting qualities *productivity* and *contamination and climate control*.

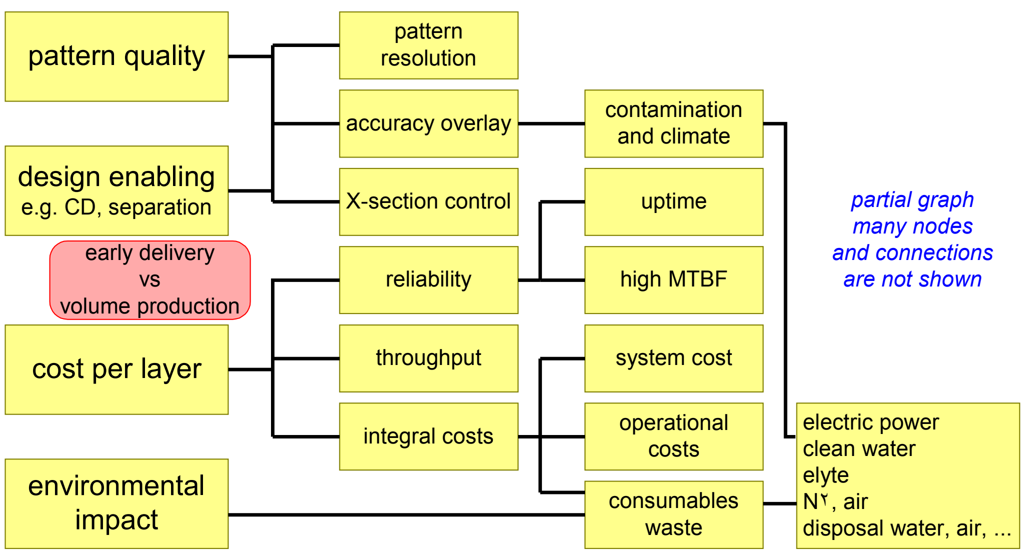

Figure 4. Customer key driver graph.

As part of the initial scan a customer key driver graph was made, see Figure 4. The main key drivers either have a semiconductor product focus or an operational focus. The pattern quality and the expanded design space are important from product perspective. The economic figure of merit in this industry is the cost per layer, currently in the order of 50$ per layer. The environmental impact gets increasingly more weight due to regulations.
Note that Replisaurus has to balance with their early customers the timely availability and the

system performance. The technology is revolutionary which increases the need for early validation. The system design has to anticipate higher performance demands in the future, while it has to accommodate early system availability for validation of the technology in actual fabs.
Figure 4 provides a further elaboration of the customer key drivers in system characteristics and functions.
During the workshop a simplified model of the fab context was made, see Figure 5. The process flow is as shown before in Figure 2 for ECPR. However, the inspection up front and the testing at the end are added. It is also shown that in dual layer cases two more process steps are performed before the results can be tested. For every step the throughput time for that step is estimated per wafer and per FOUP. These estimates provide an indication of the dimensioning of the equipment in the fab. With the targeted throughput time of the copper printing, we still need two copper printers to keep the seed sputter and seed etching cells fully occupied.

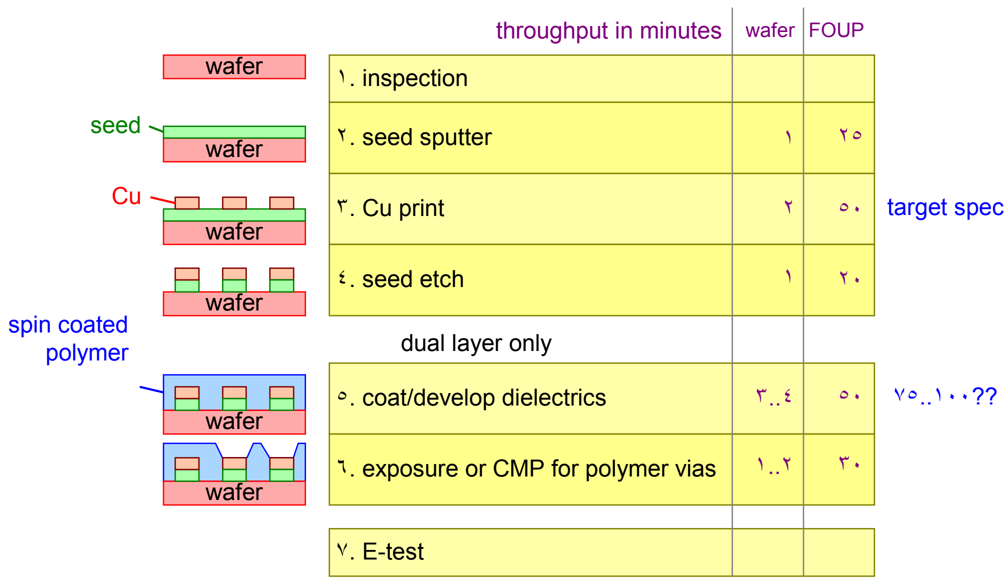

Figure 5. Process flow at fab level, from inspection until testing.

Modeling the Copper Printer

We zoomed in on the copper printer before actually making the time line in Figure 9, because we needed the cycle time of the printer. Figure 6 shows the work flow of the Copper Printer as envisioned at that moment.

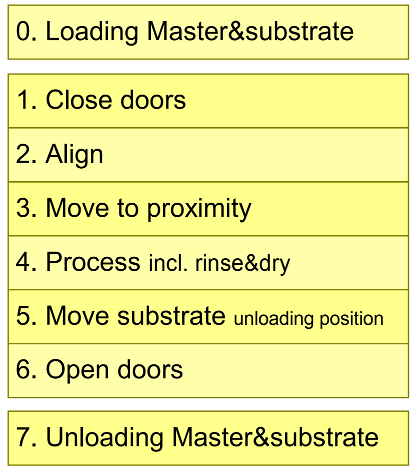

Figure 6. Work flow in the Copper Printer.

This work flow is transformed in a cycle time formula as shown in Figure 7. In fact we did zoom in further than shown here on alignment and the chamber to be able to substitute numbers in this formula. The formula is composed hierarchically to simplify reasoning about the cycle time. One of the obvious conclusions from the current numbers is that the cycle time for 50% or more is needed for non-processing activities, such as alignment, rinse & dry, and opening and closing.

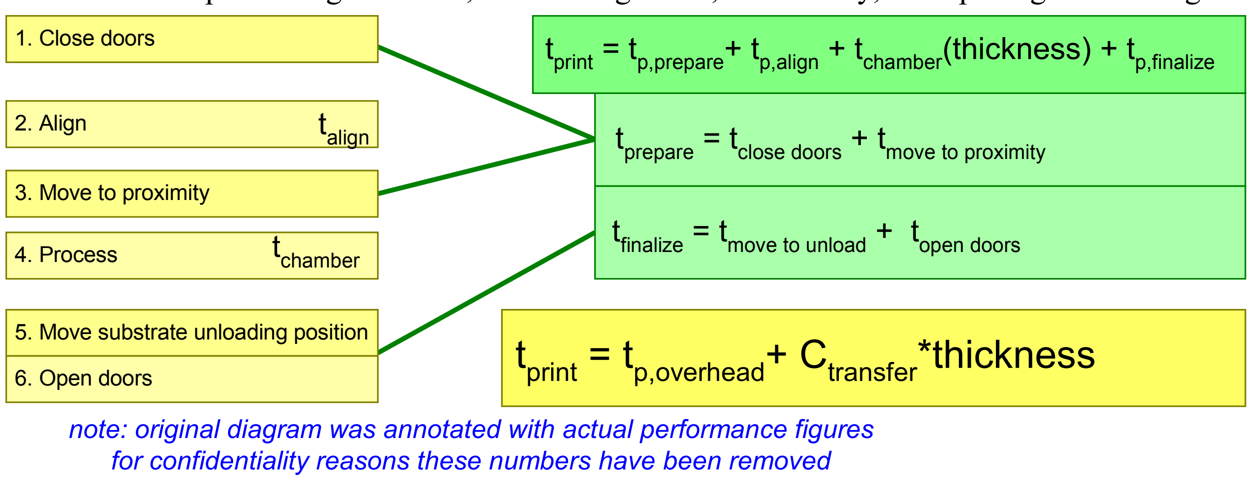

Figure 7. Formula of printer throughput time.

Modeling Alignment

The overlay (relative positioning of master and wafer) is another critical parameter for the copper printer. The overlay depends on many factors, such as the positioning accuracy of master and wafer and the reproducibility of the vertical move, on process factors, control of temperature, but most of all it depends on the alignment procedure and the optics path used by alignment.

Figure 8. Optical path to measure marker position

Figure 8 shows the optics path used by the alignment. On the master and on the wafer there are markers to facilitate alignment, see the insets in this figure. A microscope is used to magnify the marker. The enlarged image is captured by a digital camera. The dimensioning of the optics path has to balance the need for a sufficiently large field of view (so that the marker can be seen even when the alignment is far from good initially), depth of focus, and resolution (enabling accurate measurement of the marker position).

Reflection on the application of Systems Engineering

Our involvement in the Replisaurus development process has been "burst"-wise, in the form of design workshops or design reviews. The founder of Replisaurus de facto brought more continuity in the systems engineering efforts. He did have weekly or bi-weekly design and progress meetings with the design team. Our own involvement was limited to about 6 times per year, with somewhat less than half by telephone.

The main contribution of the workshops and reviews has been to "lift" the engineers from their detailed design efforts to the system and context perspective. The designers are also confronted with different concerns and considerations by zooming out.

For example the designers of the optical alignment system were focused mainly on optical and camera resolution. However, at system level the question is how accurate the position of the marker on the wafer can be determined. This accuracy is partially determined by the technical parameters such as optical and camera resolution, however the processing algorithm, the shape and characteristics of the marker itself, the positioning and stability of the microscope, and many other system parts also impact this accuracy.

The "lifting" also uncovers relations that are outside the local scope of the designer. For example, the power consumption of components results in local heating which may deform or shift parts tens of nanometers. The error budget itself is composed of many contributions in the same order of magnitude, so power consumption in the wrong places might have negative impact on positioning accuracy.

In general the performance measure of any component or function turns out to be a combination of the component itself and of its context. The context contribution is quite often insufficient taken into account. If we realize that we typical have to zoom out 6 times to get from micro level to macro level, then it will be clear that every step that we zoom out adds new insights. Systems Engineering complements Engineering by making the context information explicit.

We have shown the most outer steps of the throughput or cycle time of the system. However, to get from the description at the level provided in this paper to the level of daily design by the engineers, we need to add one or two steps more. This shows for one concern what the distance is between system operation and the engineers designing the system.

The discipline of Systems Engineering is relevant for any multi-disciplinary system. It complements the engineering focus with a systems perspective. This system perspective helps to achieve the desired system level performance and behavior in its intended context. Lack of systems engineering may cause delays at the end of the project, since the higher level dependencies become visible when the system is actually build or worse when actual operation starts.

We have customized the Systems Engineering process itself to the start-up nature of Replisaurus: time-boxed workshops and reviews. We have asked many questions rather than that we imposed structure. Main purpose of this customization is to keep the process agile, since the context is dynamic and contains plenty of uncertainties. We have used informal visualizations that fit the mental model of the engineers, rather than that we imposed formal diagrams, such as IDEF0 or SysML. In general this pragmatic Systems Engineering perspective and contribution was appreciated by engineers and managers of Replisaurus.

Summary

We have applied a customized version of Systems Engineering at the start-up company Replisaurus. Replisaurus works on an innovative copper printing process that reduces 6 processing steps in back-end semiconductor factories into one step. The context of start-up companies tend to be dynamic and its development processes tend to be full of uncertainties and unknowns.

We have shown some of the systems engineering contribution as illustration in this start-up environment. We respectively have shown the cell level, the printer level, and the alignment function, with cycle time directly related to throughput as main concern. In our meetings with Replisaurus we have discussed many more subsystems and components and many more system level qualities. The diagrams that we have used in this paper are very close to the original diagrams in our meetings. These diagrams show how we have shared the overview and system level understanding in the engineering team: with emphasis on understandability and without heavy formalisms.

The value of regularly investing time in system level discussions has been that dependencies of components became visible early in the design process. The interactive process of discussing systems engineering diagrams helped to make the engineers more aware of the system and its context.

Acknowledgments

Replisaurus has supported our research, and the writing of this paper. We were able to write this paper without many confidentiality problems, despite the competitive nature of the semiconductor domain. Especially Patrik Möller has been helpful with reviewing and suggestions for improvement.

References

[DoD 2003] DoD, *DoD Architecture Framework, Volume 1: Definitions and Guidelines*, Version 1 US Dept. of Defence, 2003.

[Fredenberg 2005] Fredenberg M., Möller P., *Recent Progress in the Development of ECPR (ElectroChemical Pattern Replication)* - Metal Printing for Microelectronics, ECS 208 Fall Meeting, Los Angeles, October 19, 2005.

[INCOSE 2007] INCOSE *Systems Engineering Handbook Version 3* (2007) http://www.incose.org/ProductsPubs/products/sehandbook.aspx (04.01.09)

[Möller 2005] Möller P., Fredenberg M., Dainese M., Aronsson C., *Metal Printing of Copper Interconnects Down to 500 nm using ECPR ElectroChemical Pattern Replication*, Micro- and Nano Engineering 2005, Microelectronic Engineering 83 (2006) 1410-1413.

[Muller 2008b] Gerrit Muller, *System Modeling and Analysis: a Practical Approach*; <http://www.gaudisite.nl/SystemModelingAndAnalysisBook.pdf>

[Muller 2009] Gerrit Muller, *Creating an Academic Systems Engineering Group; Bootstrapping Systems Engineering Research*, CSER 2009 in Loughborough NJ

BIOGRAPHY

Gerrit Muller.

Gerrit Muller received his Master's degree in physics from the University of Amsterdam in 1979. He worked from 1980 until 1997 at Philips Medical Systems as a system architect, followed by two years at ASML as a manager of systems engineering, returning to Philips (Research) in 1999. Since 2003 he has worked as a senior research fellow at the Embedded Systems Institute in Eindhoven, focusing on developing system architecture methods and the education of new system architects, receiving his doctorate in 2004. In January 2008 he became a full professor of systems engineering at Buskerud University College in Kongsberg, Norway.

All information (System Architecture articles, course material, curriculum vitae) can be found at:

Gaudí systems architecting http://www.gaudisite.nl/