Assignment in TEK4900: Technology, innovation and product development

By Furkan Kaya, MTNANO

“The evolution of the photolithography process in the semiconductor industry through innovations”

Number of words: 2864

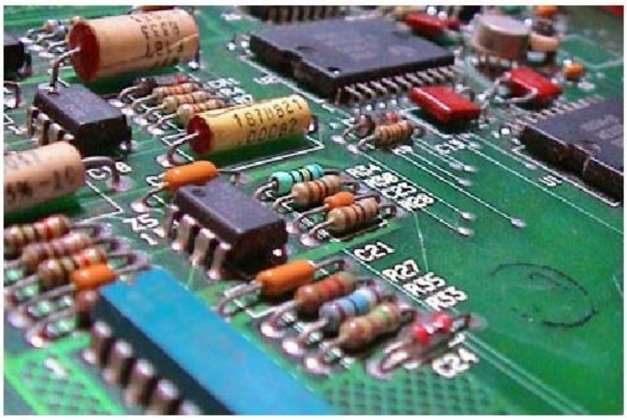

Figure 1: Schematic shows a single transistor to the left and an integrated circuit with many transistors and other necessary components to the right.[8]

Content

1. Introduction

Semiconductors are an important class of materials integral to the development of the modern electronics industry. A common semiconductor like Silicon's conductivity ranged in between the one of an isolator and a conductor (metal) makes it an ideal material for integrated circuits to be fabricated from.[1] Like all other knowledge-based innovations several separate strands of knowledge is needed for an end-product component based on the semiconducting principle.[2] However, in this essay the focus will be on the photolithographic process. This process is also known as the art of transferring patterns from a pre-defined mask and over to a material.

The first semiconductor-based component called the transistor was manufactured almost immediately after the second world war. Since then the transistor has decreased in size and more transistors now occupy a single chip. In fact, a theory postulated by Intel (a major semiconductor company) founder Gordon Moore suggests that for each 18 months, the number of transistors on a given area should double.[3] Due to the transistors being transferred by photolithography, continuous innovations are necessary for the process to follow the development required.

By looking at the evolution of the semiconductor industry through the lenses of innovation theory the intention of this text is to conduct an analysis and provide a further understanding of how the different innovations have improved the performance of modern electronic. Layout of the text is built up according to standard scientific form with an initial theoretical part providing a background for understanding rest of the text. Second section shows the evolution of the photolithographic process and section three provides an overview of the innovations throughout the history of the process. Before an analysis looking at the evolution of the photolithographic process through innovations is provided in the end.

2. **Theory**

2.1 *Background*

My interest in semiconductors and components based on them stems from my background as a nanotechnologist. In my master assignment I wrote about photodiodes based on Silicon. Since the semiconductor has shown a continuous miniaturization, a crucial task in all semiconductor research is to look at previous innovations and how innovations can continue to improve both process and product.

2.2 *Short introduction to photolithography*

This section of the text aims to give a short introduction to photolithography important to semiconductor manufacturing. Much of the information is taken from the work of M. Quirk and J. Serda.[1]

Semiconductors are a group of materials having electrical conductivities intermediate between metals (highest conductivity) and insulators (lowest conductivity). They are ideal for electronic devices due to their ability to have their conductivity varied by temperature and impurity content.

An important part of manufacturing a semiconductor device is photolithography, or the art of transferring patterns on to a material. Patterning of a semiconductor sample is done to create circuitry that define the device features and wiring. Photolithography is a 10-step process including cleaning the sample, putting on a light-sensitive material called a photoresist and baking the sample on an oven plate to increase the adhesion between resist and sample. However, the most important step of photolithography is the alignment and exposure. The sample with photoresist is aligned to and exposed by a light source going through a mask with the pattern to be transferred on.

An important parameter in evaluating the number of transistors is the resolution of the system. Resolution is defined as the ability to discern two neighbour points on the surface of a semiconductor. The resolution is dependent on the wavelength of light. Therefore, by decreasing the wavelength implicitly gives that more transistors can be placed on an integrated circuit. The smallest resolution in a system like the integrated circuit is called the critical resolution. In this text decreasing the resolution will be synonymous with decreasing the linewidth of the pattern on a semiconductor. Traditional innovations within the field have been in process and photolithographic equipment.

2.3 *Innovation theories*

Innovation theory is a broad field and a decision was made to narrow the focus to innovation theory relevant for the theme of the essay. A large bulk of this section is gathered from J. Tidd and J. Bessant's seminal work: "Managing Innovation".[4]

Most innovation can be measured according to traditional indicators. Innovation not reflected by those indicators is referred to as "hidden innovation". Examples of this form of innovation is a combination of existing technologies and processes to create new innovative ways. For more measurable innovation, there is a classification of innovation in to four categories. Adapted to our issue at hand they become:

- Product innovation: changes in an end-product transistor or other semiconductor component
- Process innovation: changes in the process leading up to manufacture of the component
- Position innovation: changes in the bulk component the semiconductor is part of
- Paradigm innovation: is a change in how people think about the semiconductors

The last form of innovation should not be confused with an another important term: technological paradigm and the term associated with it, technological trajectory.[5] Dosi's theory tries to explain why some technological developments emerge instead of others. Technological trajectory explains the direction of the progress.

In managing innovation an emphasis is placed upon whether there is an incremental or a radical innovation. An incremental innovation could be considered a minor improvement compared to a big change leading to a radical innovation. Platform innovation is a term commonly associated with incremental innovation. Basically, one has a strong basic platform that continuous incremental innovation can happen in the space around. While discontinuous innovation can be considered a type of radical innovation where either the market is completely transformed by a new semiconductor product or an entirely new process for photolithography is introduced. One could say that the rules of the game changes and a gamechanger is introduced.

Edquist and Hommen proposed an alternative way of viewing innovation, namely through an evolutionary perspective.[6] From that point of view, one views the technology as something with an end-point in existence, followed by a reproduction (meaning an offspring as in the biological definition). A mechanism introduces novelties in the system for each reproduction. These novelties could be random or predictable. A “survival of the fittest”-scenario for what novelties are introduced is implied. It can be compared to technical trajectory mentioned earlier.

3. **The evolution of the photolithographic process**

The history of photolithography has from the advent of the first transistor and up to modern day been classified according to the alignment and exposure equipment needed to achieve a certain critical resolution. As the resolution required for a product has decreased, the need for innovations in the equipment has likewise increased. In the next paragraphs this aspect will be outlined. A final section for other innovations within the photolithographic process follows in the last subsection.

Figure 2: shows a contact aligner found in the American National Institute of standards and technology[7]

3.1 *Contact aligner*

Was the primary method of photolithography until the 1970's. It was used for critical resolution of 5 micrometres and above. The pattern is put on a mask before the mask is manually aligned to the sample with a photoresist on. As the name suggests, the mask and sample come into direct contact. Then an UV-light is expected through the mask and onto the sample. The pattern is thereby transferred.

3.2 *Proximity aligner*

Evolved from the contact aligner. These types of aligners are suitable for linewidth of 2 to 4 micrometres. The mask contains the entire pattern to be transferred. But a crucial difference between 3.1 and 3.2 is that the aligner does not make direct contact with the resist. Instead it is placed very close to the sample. The reason it improved resolution was because the distance gave less scattering of light.

3.3 *Scanning projection aligner (SPA)*

Was created due to the need to avoid further resolution limitations. It was the dominant system until the early 1980’s. Their use was for resolution down to 1 micrometre. The mask-sample ratio is 1:1 and no magnitude increase is necessary. The light exposure is done by scanning the light across the surface of the sample.

3.4 *Step-and-repeat aligner (stepper)*

Is a tool for photolithography from the 1990’s. Has its name because the exposure source exposes one area at the time, before it moves on to the next area. This is due to the fact that a mask is not used anymore. Instead a component called reticle with only a fraction of the pattern is used, so that the stepper has to constantly move. The critical resolution is 0.25 micrometres.

3.5 *Step-and-scan system*

Is the most recent development. The best way of characterizing the equipment is by calling it a mixture between the SPA and stepper. A so-called hybrid tool. A reticle with only a part of the pattern is scanned on to the sample. Once the scan is completed and the pattern transfer is complete, the machine steps on the next field of exposure.

3.6 *Other improvements*

A photoresist was earlier in the text briefly mentioned as a light-sensitive material. Working principle of a resist is that it is activated by light from a certain wavelength. There are two forms of resists: positive and negative. In positive resist lithography the pattern printed on the sample is the same as on the mask, while in negative resist lithography the printed pattern is the opposite to the one on the mask.

Historically positive resists were used, but as the development reached the submicron (under 1 micrometres) resolution some innovation was needed and the industry began using negative resists. They were of different materials compared to positive resists.

4. The development seen through innovation theory

Before proceeding with section four, some clarifications are necessary. In the topic question the product is considered to be the semiconductor sample after it has been processed. Meanwhile the process is the photolithographic process described earlier in section 2.2.

The development throughout the years definitely show some incremental changes in the product. “Small” improvements in resolution is seen for each time-period/equipment-period. Meaning that both product and incremental innovation can be seen. With those important aspects validated, platform innovation can be assumed. The platform in this regard is obviously the semiconductor end-product component with continuously decreasing linewidth/resolution.

Another platform is the photolithographic process having the working principle of transferring pattern to a sample. The basic principle of process is the same, but some variations can be seen since new tools are introduced. The aligners have had continuous incremental changes in how they function. In some instances, there have been large transformations in the tools. However, it has not led to big changes in the actual process of photolithography. The process has only experienced small, incremental innovation.

In section 3.6 the focus is on the photoresists rather than the aligner systems. The transformation from positive resist to negative resist must be a radical innovation. Going from printing the same pattern on the mask to printing the opposite is a drastic measure and the fact that it decreases the resolution further confirms this. An ingenious approach that prolonged the life of Moore’s law for several decades.

Some discontinuity is seen since positive resists are not used anymore for submicron lithography. Most modern electronic devices require submicron patterning. But in some cases, the resolution demands are above the submicron threshold. In those events positive resist is still preferred. That suggests only a partially discontinuous innovation.

5. Analysis

Some analysis was done in the previous section. Section 5 will look at this in further depth.

The proximity aligner was clearly a reproduction of the contact aligner. An evolutionary path is seen between them. With the SPA more changes are seen. A scanning component is inserted into the aligner system, but other main aspects are still the same as in earlier aligners. The stepper goes away from the scanning element and introduces a reticle with only a part of the pattern. It could be considered a radical innovation due to its revolutionary ways. However, it is also evolutionary compared to the other system due to the working principle staying the same.

As mentioned in 3.5, the newest development in the photolithographic process is a step-and-scan system merging the two technologies of SPA and stepper. According to a denotative meaning of the term "hidden innovation" this innovation should be classified as such. Though one could as easily characterize it as an incremental innovation based on factors like a small, stage-wise improvement and the fact that merging them leads to entirely new properties for the aligners.

The two paragraphs above in this section shows that despite the photolithographic process as a whole only experiences small incremental changes in improved resolution, there are aspects of the process that experience radical innovation. These radical innovations include both the change of photoresist and aligner and exposure systems based on partially new working principles (to avoid confusion: meaning the scanning element of the SPA).

By using Dosi's theories it can be seen that the technological development has been driven by the constant need for improving the resolution. Rather than focusing on other aspects in the photolithographic process that might decrease cost or practability, the focus has been on improving the resolution to fulfil the need for more transistors on an integrated circuit. This is implicit also when evaluating the technological trajectory of process.

The evolutionary and reproducibility in the innovation in the photolithographic process has already been seen. A mechanism to introduce novelties for each reproduction is also seen. This mechanism is either controlled by a semiconductor company or a research group. In section 3 both random (SPA and stepper) and predictable (contact and proximity aligners) novelties were introduced. It shows a “survival of the fittest”-scenario in the use of aligner-systems where when one reaches a critical resolution limit, the usefulness of a system ceases to exist. Implying that both a technological trajectory and a survival of the fittest is present.

One age-old conundrum in economic thinking is the incremental product-introduction done by companies. In many ways the overall society would benefit from a more radical innovative approach. Transferring this to our topic in question, the question becomes whether the photolithography process and the semiconductor components created by it would benefit from skipping a step or two in section 3. This is negated by the lack of competency. The knowledge in semiconductor manufacturing is very industry-specific (and even company-specific due to the market dominance of a couple of companies).

Despite the societies overall benefit from decreasing resolution, increasing the number of transistors and from that the computing power, the wished development was not feasible from a technological perspective. This further gives inclination to further belief in the evolutionary theory by Edquist and Hommen. Buoyed by the belief that an incremental innovation was the only possibility.

Two forms of innovation theories not yet used in this essay are position and paradigm innovation. Having in mind how they were defined in section 2.3, the bulk component based on the product manufactured by the photolithographic process like a personal computer has experienced small changes in its functionality besides the increase in computing power due to the increased number of transistors. Overall function of the computer is almost unchanged, meaning reading algorithms and calculating. Although the quality of the products stemming from these algorithms have improved significantly. Paradigm innovation can be used to explain the advent of the first computers for example, where the semiconductor found a whole new use. People's view of the semiconductor though is largely unchanged in the last three decades or so.

6. Conclusion

A scientific overview of the photolithographic process for manufacturing semiconductor components have been conducted in this essay.

It was seen that the photolithographic process development has been both incremental and evolutionary. The semiconductor-based products showed an incremental change. Aspects of the process like exposure equipment (aligners) and photoresists, on the other hand, showed radical change when critical resolution limits were reached.

7. Literature

[1] Quirk, M. and Serda, J. *Semiconductor manufacturing technology*; Pearson Education Limited: New Jersey, USA. 2001.

[2] Drucker, P.F. *The discipline of innovation*, Harvard Business Review. 1998

[3] Britannica. *Moore's law*. Retrieved from: https://www.britannica.com/technology/Moores-law

[4] Tidd J. and Bessant J. *Managing Innovation – Integrating technological, market and organizational change.* Wiley: West Sussex, United Kingdom. 2017

[5] Dosi, G. *Technological paradigms and technological trajectories.* 1982

[6] Edquist, C. and Hommen, L. *Systems of innovation: theory and policy for the demand side.* Technology in Society. 1999

[7] National Institute of standards and technology. *NanoFab Tool: Suss MicroTec MA8 Contact Aligner.* Retrieved from: https://www.nist.gov/laboratories/tools-instruments/nanofab-tool-suss-microtec-ma8-contact-aligner

[8] Creatron inc. *2N6039 – NPN Darlington Power Transistor (80V 4A). Retrieved from: https://www.creatroninc.com/product/2n6039-npn-darlington-power-transistor-80v-4a/*