# The Nature of Technological Knowledge: Extending Empirically Informed Studies into What Engineers Know[1]

Dr. Marc J. de Vries
Eindhoven University of Technology

## 1. The relevance of philosophical reflections on the nature of technological knowledge

Not many philosophical studies have yet been written about the nature of technological knowledge. In the field of epistemology the standard definition of knowledge as 'justified true belief' is often taken as the starting point. There is, though, a lack of studies in which this definition is explored with respect to technological or engineering knowledge. In particular the question of how intentionality and normativity, important aspects of technological knowledge, fit in with this proposition-oriented definition has not yet been answered ~~yet~~. This, no doubt, has to do with the fact that, generally speaking, reflections on the nature of technology still receive little attention in philosophy. Reflections on the nature of technological knowledge therefore can contribute to our general understanding of the concept of knowledge and thus contribute to the emancipation of the philosophy of technology within the discipline of philosophy.

Apart from this philosophical relevance, philosophical reflections on the nature of technological knowledge can have practical relevance for other disciplines. Two examples of that can be mentioned here. In the first place there is the field of knowledge management. In this field one often does not seem to differentiate between different kinds of knowledge. Some authors (e.g. Hitt, Ireland and Lee 2000) take as a starting point the standard definition of knowledge as 'justified true belief', but do not take into account that in the case of technological knowledge that definition may not be the best representation of technological knowledge. The same is true in the field of education, and in particular education about technology. Differences between the nature of technological knowledge and other types of knowledge, as well as differences between different types of technological knowledge, should be taken into account when it comes to the transfer of technological knowledge.

## 2. Different viewpoints for reflecting on technological knowledge

In his survey of the philosophy of technology, published in the book 'Thinking Through Technology', Carl Mitcham identified 'technology as knowledge' as one of the four ways of considering technology (the other three ways are: technology as artifacts, as activity, and as volition). In his chapter on technology as knowledge, Mitcham summarises the main outcomes of philosophical studies in this field. It appears that not that much has been published in this respect. Several philosophers wrote about the fact that technology cannot be described adequately as 'applied science'. Nowadays, most philosophers of technology accept the idea that technological knowledge is different from scientific knowledge. But how it differs from scientific knowledge has not yet been described in much detail. The same conclusion is drawn in another synthesising book by Subrata Dasgupta. For philosophical reflections on the nature of technological knowledge Mitcham mentions at least two fields that can be used as a source of inspiration. The first is the history of technology. Philosophers' interest in drawing from this field can be related to what is called the 'empirical turn' in the philosophy of technology. Apart from the history of technology, a lot of studies into technological knowledge, and in particular the role of technological knowledge in design processes, have been done in the field of design methodology.

It would go beyond the practical limitations of this paper to give a more complete survey of existing literature about the nature of technological knowledge than Mitcham's and Dasgupta's. Instead some examples of authors in the fields of history and design methodology will be mentioned for each field to show what kind of ideas have developed in the past. These are just examples and no claim of completeness or representativeness is made here. The main motive for including this section in the paper is to show that confrontation of what has been written in these fields with existing philosophical reflections can offer interesting perspectives for new reflections on the nature of technological knowledge. Also, some philosophers that were not yet included in Mitcham's survey will be mentioned with respect to that confrontation.

So, in the first place, we can find historians who have reflected on the nature of technological knowledge. As mentioned before, in the philosophy of technology an 'empirical' turn is taking place. Philosophers have developed an interest in reflecting on empirical data about technological developments. According to Rachel Laudan, such material is generated not in the least by historians. Two names in particular should be mentioned here: Edward Constant and Walther Vincenti. Both have been involved in studying the development of flight technology. Both Constant and Vincenti have emphasised that it is not only scientific knowledge that plays a role in engineering design (other historians had made the same statement before, e.g. Edwin Layton, Michael Gorokhov, and Henryk Skolimoski) but that there is a body of knowledge, different from science, which is used by engineers in their design work. Vincenti made an effort to classify the different types of knowledge that aircraft engineers used. According to him engineering design knowledge can be fundamental design concepts (operational principles and normal configurations), design criteria and specifications, theoretical tools (mathematics, reasoning, laws of nature), quantitative data (descriptive and prescriptive), practical considerations and design instrumentalities ('procedural knowledge'). He also identified the origins of these types and knowledge and found that science makes a very limited contribution to the engineers' knowledge and that the design process itself is also a knowledge generating activity.

In the field of design methodology, too, reflections on the nature of the knowledge that is used in design processes have been published. One of the oft-cited contributions in this respect was made by Nigel Cross in his Design Studies article 'Designerly Ways of Knowing'. Cross in that article focuses on the problem solving skills and their tacit character (that type of knowledge seems similar to what Vincenti called 'practical considerations'). Another well-known contribution to this field is Donald Schön's book 'The Reflective Practitioner' (1983). Here, too, we see a concentration on process-oriented skills (the epistemology of reflection-in-action, in Schön's own words). Nigan Bayazit is an example of an author who took a broader view by referring to the distinction between procedural and declarative knowledge. In addition, Bayazit mentioned normative knowledge (preferences, values, tastes, attitudes) and collaborative design knowledge. Bayazit does not define this last category but only points out that knowledge development of individuals collaborating in a group is different from knowledge development of individuals working alone.

Perhaps, surprisingly, the discipline that seems to have a backlog in theories about technological knowledge in design, is philosophy. This is probably due to the fact that in the past technology has not had much attention in the mainstream of philosophical debates. The philosophy of technology is a fairly recent field within philosophy, at least more recent than, for example, the philosophy of science. There has not yet been much serious effort to seek for ways of applying philosophical theories about knowledge to technology. One of the few philosophical efforts to classify technological knowledge was made by Günther Ropohl in 'What Technologists Know and How They Know It' (a title that refers to Vincenti's book 'What Engineers Know and How They Know It'[2]). Ropohl – like Vincenti – defines a number of categories of technological knowledge: technological laws, functional rules, structural rules, technical know-how and socio-technical understanding. At first sight, there seems to be a fair amount of overlap between Ropohl's and Vincenti's categories. Only Ropohl's socio-technical knowledge category, according to himself, is missing in Vincenti's analysis. Ropohl is not an epistemologist and does not refer to epistemological debates on the nature of knowledge. Davis Baird has called attention to the 'thing-y-ness' of things and, related to that, for what he called 'thing knowledge'. According to him in the philosophy of technology material aspects have not sufficiently been taken into account. Taking these into account would pose an interesting question to classical epistemology, namely, the question whether or not thinking about innovations in the material realm is adequately described by defining knowledge as 'justified true belief'. Reflecting on the knowledge of artifacts in technology may well cause us to propose revision of this definition. Randall Dipert already pointed out that in an epistemology of artifacts rationality in our attitude towards artifacts is less a matter of having true beliefs by the most reliable criterion available than a certain usefulness in regarding them to be a certain way.

We have seen examples of authors in different disciplines who have reflected on the nature of technological knowledge. We noticed historians who provided empirical data, design methodologists who focused on the skill-types of knowledge that are involved in design, and philosophers who in an 'empirical turn' have started to exploit the empirical case study material. We also saw several efforts to define categories of technological knowledge. It is striking that there is not much cross fertilization between the fields mentioned above (philosophy, history and design methodology). Each has its own academic journals and international research networks. A comparison between the different approaches would be an interesting impetus for a new research.[3] A second impetus for new research may be found in confronting what has been written about the nature of technological knowledge so far with the definition of knowledge as 'justified true belief'. Mitcham briefly referred to that definition, but did not yet compare it with the categories he collected from the other authors. Comparison of this definition with what has been stated about technological knowledge in other views (see above) immediately raises interesting questions about this 'standard' definition of knowledge. We already mentioned Davis Baird's view on 'thing knowledge' and Randal Dipert's remark about usefulness rather than truth being a criterion for our beliefs about artifacts. One could question how the intentional and normative aspects of engineers' and designers' knowledge would fit into the standard definition of knowledge. Can knowledge about the purpose and functioning of an artifact be described as 'justified true belief' or is it of a different nature? And what about the knowledge to determine if an artifact is 'successful' or not? Michael Polanyi has defined the concept of 'skills' and Gilbert Ryle has written about the difference between 'knowing that' and 'knowing how', whereby the last type of knowledge is closely related to Polanyi's 'skills'. Many of these 'skills' have the property of being 'tacit'. It can be questioned here too if such knowledge complies with the definition of 'justified true belief'. It seems that various questions emerge when the 'standard' definition of knowledge is applied to technological knowledge and ample opportunities for further reflection show up here.

## 3. Toward a research agenda on the nature of technological knowledge

There are at least three ways of making progress in the study into the nature of technological knowledge. In the first place, it would be worthwhile to draw a comparison between the different approaches through which the nature of technological knowledge has been studied so far: the historical, the design methodological and the philosophical. In the second place, the work of Vincenti, that so far has been one of the most promising in terms of exploiting empirical data for philosophical reflections, was limited because it only dealt with one particular field of engineering, namely aeronautic engineering (the design of aircraft). It would be interesting to see how Vincenti's categories for engineering knowledge ('what engineers know') and the ways through which those are obtained ('how they know it') would stand in comparison with entirely different fields of engineering; for example, the design of Integrated Circuits. In this paper a first case study in that field will be elaborated, namely the LOCOS technology for making transistors and ICs. This approach fits well with the 'empirical turn' in the philosophy of technology. Another aspect that makes the LOCOS case different from Vincenti's cases is that it does not deal with an object (a product such as an airplane) but with a structure in a material. In the third place, we see that there is a lot of attention paid nowadays to the integration of technical and social aspects in design. Products not only have to function well (whereby the laws of nature determine what is feasible and what is not), but they also have to meet the customers' needs and other social requirements (e.g. legislation with respect to product safety). Engineers and designers have to integrate knowledge of all those different aspects. This awareness has had a large impact on the way engineers and designers work nowadays and the way in which they are educated. It is hardly known, though, what 'integration' exactly means. How can we know that these different types of knowledge have been integrated? How can we assess whether or not this integration was successful? Such questions are most relevant in many contemporary situations, in which the need for this integration is well recognised. In this paper, such questions will not yet be addressed. They are only mentioned to point to other research challenges in the field of philosophical reflections on technological knowledge.

## 4. The LOCOS case study

### 4.1 Background of the LOCOS case study

LOCOS is the acronym for LOCal Oxidation of Silicon. This is a technique for making transistors and integrated circuits on silicon substrates. It was invented and developed at the Philips Natuurkundig Laboratorium (the central physics laboratory at the Philips company, a multinational company that has its headquarters in the Netherlands and is well-known for its products in many fields, such as consumer electronics, medical equipment, electronic components, household equipment and its original product, light bulbs; in the USA, Philips products are often marketed under brand names such as Magnavox and Norelco). A recent historical study into the history of this laboratory (De Vries 2002), which is also known as the Philips Nat.Lab., has shown that different types of research work were done there in the course of time, ranging from what was often called 'fundamental' research to very practical trouble shooting. Particularly in the 1950s and 1960s, there were many debates about the desirable balance between 'fundamental' and 'applied' research in the Nat.Lab. research program (De Vries 1999). In 1947, the transistor was invented in the Bell Labs. This invention, to a large extent, was the result of applying solid-state physics to electronics and, therefore, has often been mentioned as a confirmation of the industrial relevance of conducting 'fundamental research'. But the LOCOS case study shows that much of the development work in the field of transistors and ICs at Philips was more practical than the term 'fundamental research' would suggest. Both the term 'fundamental research' and the term 'applied research', which we find in the Philips Research managers' debates, appear to be ambiguous when we examine the examples that are mentioned in these debates and one should be careful in interpreting them. Yet, they indicate that in the research program different types of research studies were distinguished. It would be an interesting topic for reflection to see if these different types of research studies are somehow related to different types of technological knowledge that result from them, but in this paper this will not be elaborated on.

Before starting the description of the invention and further development of LOCOS it is useful for those readers who are not acquainted with integrated circuit terminology to explain some basic concepts first[4]. This will help them to grasp at least the essentials of the LOCOS technology.

Solid-state transistors and integrated circuits have replaced the amplifier tubes. They are produced by bringing in ('doping') elements ('impurities') with an abundance of electrons or with a lack of electrons ('holes') into semiconducting materials (mostly germanium or silicon). This results either in 'p-type' material that has an abundance of positive charge carriers, or 'n-type' material that has an abundance of negative charge carriers. The transitions between the two types are called 'junctions'. Regions of p- and n-type material can be separated by insulating layers of silicon oxide. The structure is covered by a protecting layer (the 'passivation layer'). Transistors, in which mobility of both the positive and the negative charge carriers is used are called 'bipolar transistors'. 'Unipolar' or 'field effect transistors' use only the mobility of either positive or negative charge carriers.

The standard way for creating structures of p- and n-type regions is called 'planar technology'. A silicon substrate is oxidized so that a layer of silicon oxide is created, with part of this layer is etched away (the parts that are not supposed to be etched away, are masked off; for that some technologies are available, of which the lithographic process is a well-known). Through these 'windows' dopant impurities are introduced into the silicon. Then another oxide layer is grown and new windows are created, through which again at certain places dopant impurities can be introduced. Thus several layers of ~~n- and p-type~~ p- and n-type silicon can be made.

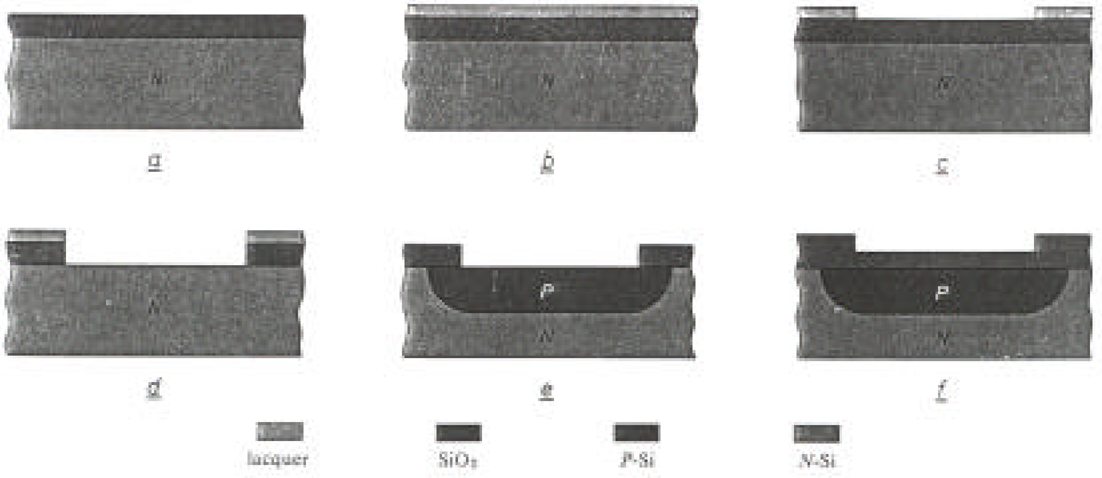

Fig. 1. Schematic representation of various steps in making an integrated circuit by the planar technique, the processes being oxidation, masking and diffusion (the diagrams are not to scale).

a) A silicon dioxide film is formed by oxidation on a crystal wafer of *N*-type silicon.
b) A coating of photosensitive lacquer is applied.
c) An opening is etched into the coating of lacquer by a photolithographic process.
d) The oxide underlayer is etched away.
e) The remaining lacquer film is removed by chemical agents, after which the wafer is heated in an atmosphere containing boron. This diffuses into the crystal to form a zone of *P*-type silicon.
f) The opening in the $SiO_2$ layer is sealed off by a further oxidation process.

Figure 1. Planar technology (from Philips Technical Review, Vol. 27, No. 7, p. 193).

### 4.2 Main steps in the development of the LOCOS technology

In this section, firstly, a historical description of the invention and development of LOCOS in a number of steps will be presented[5]. In section 4.3 we will again go through this same sequence of steps and examine what types of knowledge we find in each of those steps.

The invention of LOCOS can be mentioned as a good example of the role of serendipity in technological developments. In 1967, Dr. Else Kooi, a chemist who had joined the Nat.Lab. in 1958, was not at all looking for a new way of making flat semiconductor structures in silicon when he found out that a layer of silicon nitride ($Si_3N_4$) protected an underlying silicon layer from oxidizing. To the contrary, he had hoped that the underlying layer had oxidized because he had heated a silicon substrate covered by a silicon nitride layer to see if a silicon oxide ($SiO_2$) layer would grow. This thermally grown silicon oxide layer would make a better interface with the silicon nitride layer than a (vapor) deposited layer. The nitride layer was important for masking against impurities and as a protection against corrosion (the passivation layer). To his surprise, though, Kooi found that only the backside of the silicon substrate, where there was no silicon nitride, had oxidized. Immediately, Kooi realized the possible impacts of what he had found by accident. By heating silicon that was only partially covered by silicon nitride, he could grow silicon oxide precisely at places where there was no silicon nitride. Removing the silicon nitride would then leave a semi-conducting structure that was very flat because the silicon oxide had sunk halfway into the silicon substrate (silicon nitride has 2.2 times the volume of the silicon it originates from). That was useful because in the production of semi-conducting devices the main rule was: the flatter, the better (this results in more reliable interconnect patterns). Besides that, the sunken silicon oxide would also serve as a good separator (insulator) between the areas left and right from the silicon oxide layer. That too was useful, as good insulation is another important requirement for reliable semi-conducting structures. The combination of these two properties made Kooi recognize the potential of his finding. From then on the story of LOCOS is a continuous struggle with a series of problems that Kooi faced when trying to apply the LOCOS technology for making semi-conducting devices on silicon substrates.

In figure 2, the principle of the LOCOS technology, as it was ultimately published after the series of problems had been solved, is shown. The first problem was etching away the silicon nitride after the oxidation process. Apart from hydrofluoric acid nothing seemed to remove the silicon nitride, but that also removed the silicon oxide. Then Kooi remembered that in a previous experiment he had used lead oxide (PbO) as a catalyst to make oxidation occur at low temperatures. When he did the same in the LOCOS process he found that the resulting lead glass could easily be dissolved in diluted hydrofluoric acid, which did not hurt the silicon oxide.

The second problem was the occurrence of cracks in concave corners of LOCOS structures. This problem emerged when LOCOS was used to produce an array of diodes for a vidicon television pickup tube. Several of the diodes appeared to leak, which was the cause of white spots in the video pictures. By oxidizing more severly than necessary Kooi found out that silicon oxide spots would grow in defects in the silicon nitride film and lift up the edge of the silicon nitride (as a chisel would do) thus causing mechanical stress that resulted in cracks in the concave corners. A solution was found in creating a thin silicon oxide layer between the silicon and the silicon nitride (by thermal oxidation). This extra layer reduced the effects of silicon oxide spots in silicon nitride defects.

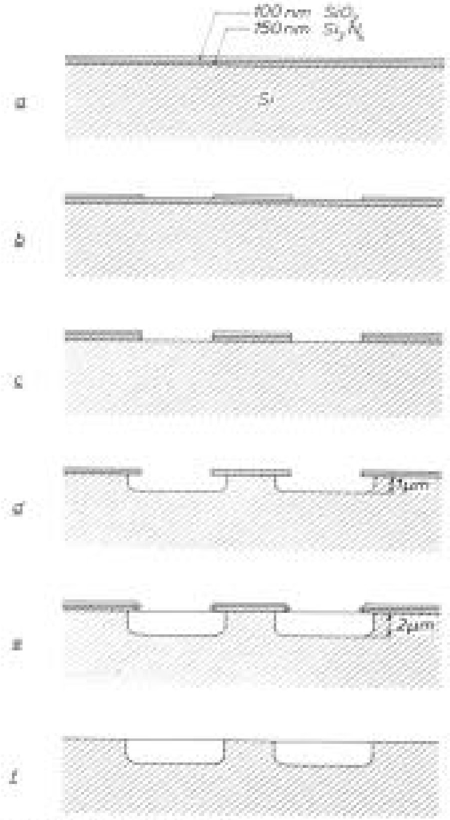

Fig. 12. The LOCOS technique.
a) A layer of silicon nitride and a layer of silicon dioxide are successively formed on the silicon.
b) A pattern of holes is etched in the $SiO_2$ using the conventional photo-etching technique.
c) The pattern is etched into the $Si_3N_4$ with hot phosphoric acid, the $SiO_2$ serving as a mask. $SiO_2$ masking is required because the photo-lacquers normally used for masking are attacked by hot phosphoric acid.
d) The silicon is etched away at the holes in the pattern to a depth of about 1 µm.
e) The silicon in the 1 µm deep holes is oxidized to a depth of about 2 µm. The holes are completely filled with the $SiO_2$ thus formed. The $Si_3N_4$ is only superficially oxidized.
f) All $Si_3N_4$ is etched away with hot phosphoric acid.

Figure 2. The LOCOS technology (from Philips Technical Review Vol. 31, No. 7/8/9, p. 234).

The third problem was known as the 'bird beak' and 'bird head' problem. These names were given by Jo Appels, one of Kooi's assistants, who had come up with a method to produce slices of LOCOS structures that could be inspected through a microscope. Beaks and heads are structures that emerge when growing $SiO_2$ surrounded by other structures seeks a way out. These beaks and heads, of course, disturb the flatness of the overall structure. Kooi's intuitive response was the desire to 'shave off' such beaks and heads. It would take several years until a way was found to fulfill that desire and etch them off (namely by first depositing a borate-phosphate-silicate glass layer over the beak or head and then etching away both this layer and the underlying beak or head). Alas Kooi's accounts of the LOCOS development do not inform us about how he found that solution.

The forth problem was the 'white ribbons' that appeared along the LOCOS structure edge. From scanning electron microscope images of these ribbons, Kooi could derive that they had to be narrow regions of non-oxidized silicon. This puzzled Kooi, because there was no obvious reason why the silicon did not want to oxidize at those places. Kooi's assumption was that somehow masking material at those spots had covered the silicon. Silicon nitride was, of course, the first option for that material ~~of course~~. But how could it get there? To explain that Kooi came up with a model in which nitrogen transfers from the nitride oxidation mask to the interface between the silicon and the silicon oxide. Near the LOCOS edge not much nitrogen would react with silicon because of the competition of the oxidation reaction, but at some distance from the LOCOS edge, the nitrogen could well form new nitride and serve as a mask, thus causing the formation of the 'white ribbons'. If the nitride ribbon was not removed, oxidation in that area would not be effective. Experiments were done to confirm this. Kooi's solution to the ribbon problem was to over-etch so that not only the nitride oxidation mask would be removed but also the nitride at the ribbon site. This solution was inspired by the previous experience that the ribbon effect had not happened when some over-etching had occasionally been applied.

The story of the development of LOCOS in Philips does not quite end here, but we already have sufficient material for reflection on the nature of the technological knowledge in this case study. Now we will try to identify what types of knowledge can be distinguished in the steps that have been described above.

### 4.3 Types of knowledge in the LOCOS case study

Let us now consider what knowledge was used by Kooi to take each of the hurdles that we have seen in the LOCOS story (as described in section 4.2). The first step in the process was the recognition of the potential of silicon nitride to serve as an oxidation mask for silicon substrates. In 1966, Kooi was able to make a connection between several things he knew. By inspecting the heated substrate, Kooi had observed that the silicon under the silicon nitride had not oxidized. From this he derived that the nitride had protected the underlying silicon against oxidation. This he related with the function of a mask. He knew that masks were used to make oxidation patterns on silicon substrates (this was the basic principle of planar technology). He knew that silicon oxide has stabilizing properties that make it suitable to function as a protecting coating, as had been found by Atalla, Tannenbaum and Scheibner in a 1959 paper that Kooi knew and had inspired him to do his own Ph.D. work on the surface properties of oxidized silicon (in 1967 he got the degree). He also knew a material property of silicon nitride, namely that it was a better protector against invading impurities during oxidation than silicon oxide was. Finally, he knew that silicon oxide had twice the volume of the original silicon and therefore would sink halfway into the silicon substrate. This would make a rather flat surface, which was good for planar structures (it allowed for better contacts with the metal strips that were to be put onto it). All this knowledge together made Kooi realize that using silicon nitride as a mask for making oxidation patterns in silicon oxide would yield rather flat and stable surfaces with few impurities. Those properties fit~~ted~~ well with the generally recognized requirements for a planar transistor. He was now able to imagine a process that would result in such a planar structure.

Evidently, this is quite a rich combination of knowledge and that is what makes the invention so impressive. Part of the knowledge has to do with the (intentionality-bearing) function that a material can fulfill. This knowledge could be 'functional nature knowledge', because it is related to the 'functional nature' properties of the material. In Meijers' terminology, these belong to the relational properties of the artifact (or material in this case; see Meijers 2000, p. 84). An example of this type of knowledge is Kooi's insight into the functioning of a mask in planar technology. Part of the knowledge has to do with material properties. This knowledge refers to the physical nature of the material and can be expressed in propositions such as 'impurities do not easily invade into silicon nitride at high temperatures'. This can be called 'physical nature knowledge'. Then there is knowledge to judge whether a material property is suitable for a planar structure. For instance, the fact that silicon oxide sinks halfway into the silicon is good from a flatness requirement point of view, or the fact that silicon nitride shields off underlying silicon from oxidation makes it suitable for serving as a mask in planar technology. This can be called 'means-ends knowledge'. The knowledge about how to set up a process to produce a planar transistor using the newly found combination of properties (first deposit silicon nitride, then oxidize, then remove the nitride), in other words, the knowledge about what actions will lead to the desired result, can be called 'action knowledge'.

This first step of the LOCOS process was probably the most crucial and we have seen that it involved quite a rich combination of knowledge. The next steps required combinations of knowledge also, but were less rich. As we saw the first problem that Kooi met when he tried to control the process of LOCOS, was his unability to etch away the silicon nitride without hurting the silicon oxide. To solve this problem, Kooi made use of previously gained knowledge. From previous experiments in his Ph.D. research he knew that the presence of lead oxide made silicon oxidize at lower temperatures. He had picked up that idea from a 1961 article by Kallander, Flaschen, Gnaedinger and Lutfy. Oxidation under low temperatures was attractive because it prevented already formed junctions between p- and n-regions to be disturbed because of the increasing mobility of the donors and acceptors at higher temperatures. The lead oxide causes lead glass to be formed and this glass can easily be etched away with the nitride without hurting the silicon oxide. Kooi remembered this when he was struggling with the removal of nitride in the LOCOS process. Again we see a combination of knowledge. Kooi knew that the presence of lead oxide made oxidation of silicon happen at lower temperatures ('physical nature knowledge'). He recognized that therefore the lead oxide could serve the function of a catalyst in his LOCOS process ('means-ends knowledge'). He then also knew that the action of adding lead oxide would enable him to complete the LOCOS process ('action knowledge').

In solving the second problem, the occurrence of cracks in concave corners of LOCOS structures, no knowledge of material properties or of functionalities was involved. Kooi just guessed that creating an extra thin oxide layer would make a better geometry of the structure in which less tensions could emerge in the silicon nitride edge. Here the emphasis seems to be on knowing that the action of creating the extra layer would have a positive effect ('action knowledge').

The third problem, 'bird beaks' and 'bird heads' was again solved just by imagining a simple action, namely by just 'shaving off' the undesired structures. Here too 'action knowledge' seems to be an appropriate characterization.

For solving the fourth problem, the 'white ribbons' that appeared along the LOCOS structure edge, Kooi developed a model that involved knowledge of the behavior of silicon, namely that it rather oxidizes than reacts with nitride when both oxygen and nitride are present. This is what we previously called 'physical nature knowledge'. His solution was inspired by a previous experience that at that time was not yet related to the 'ribbon' problem, namely, that over-etching would not only remove the nitride oxidation mask but also the nitride. Applying this previous experience to the new problem required recognition of the function of over-etching in such a case ('functional nature knowledge').

'Means-ends knowledge' is involved in all the steps because all problems have to do with the fact that unexpected phenomena create a conflict between the structures resulting from the LOCOS process and the generally recognized requirements for planar structures such as good insulation between differently doped regions, good stability, and flatness of the surface. One could say that 'means-ends knowledge' played a role in the recognition of the problems. Because Kooi knew what the properties of a planar structure should be, he was able to judge if his LOCOS-made structures were 'good' or 'bad'.

### 4.4 Comparison with Vincenti's categories

As the purpose of the LOCOS case study was to extend Vincenti's empirical studies into new technological areas, an obvious continuation for reflecting on the empirical data is to see if Vincenti's categories of engineering knowledge apply here too.

Vincenti's first category consists of what he called fundamental design concepts. In the LOCOS case we can recognize this as Kooi's knowledge of what – in general – a planar structure is. Although Kooi evidently had this knowledge, it only plays a role in the background. It only seems to become relevant when criteria and specifications are derived from this. But this is a different category in Vincenti's view. This category in the LOCOS case comprises the knowledge that planar structures need to be flat, that the threshold voltage of the transistor structure needs to be sufficiently high, that dimensions should be small (because the main aim is to make small structures), and that the structure should be stable. Vincenti's category of theoretical tools is present in Kooi's knowledge of the material properties of silicon, silicon oxide, silicon nitride and lead oxide, but also in his ability to reason from the properties towards using those for a certain purpose. Vincenti distinguishes two types of quantitative data: descriptive and prescriptive. Both are not very clearly present in the LOCOS case. Kooi does experiment and measure (for instance C-V curves that represent the relationship between the transistors capacity and voltage, layer thickness, deposition and oxidation temperatures), but he does not seem to make much use of exact data. He seems to be more interested in 'more' or 'less' than in 'exactly how much'. Practical considerations, Vincenti's next category, are present throughout the story. The idea of shaving off the beaks and heads can be mentioned as an example of it. Finally, there are the design instrumentalities (or procedural knowledge). These are to a certain extent equal to what has been rephrased into 'action knowledge' and we have seen several examples of that.

The comparison shows that Vincenti's categories also can be used to make a survey of the various types of knowledge that were involved in the invention and further development of the LOCOS technology. The types of knowledge ~~as~~ used in Section 4.2 can be related to Vincenti's categories as follows. The 'physical nature knowledge' category combines Vincenti's categories of theoretical tools (as far as knowledge of scientific laws is involved), and quantitative data (descriptive). It is knowledge of the natural properties of the material or artifact. 'Functional nature knowledge' relates to Vincenti's categories of fundamental design concepts and practical considerations. This is knowledge of what a material or artifact can be used for. The 'means-ends knowledge' comprises Vincenti's criteria and specifications, and his prescriptive quantitative data categories. This type of knowledge refers to whether or not a material or artifact is fit for the intended function. 'Action knowledge' is similar to Vincenti's theoretical tools (as far as reasoning and the use of mathematics is concerned) and his design instrumentalities. It refers to knowledge about how to perform actions that lead to desired outcomes.

The categories as proposed in this paper are not meant to complement Vincenti's categories, but to offer an alternative. The advantage of the categories as suggested in this paper is that they can make a bridge to the philosophical terminology that is used, for instance, by philosophers who studied artifacts from an action theory point of view. The terms 'physical nature knowledge' and 'functional nature knowledge' refer to the 'dual nature of technical artifacts' research program (see Kroes and Meijers 2000, note 6), in which action theory plays an important part. The term 'means-ends knowledge' refers to the term 'means-ends beliefs' that was used by Dipert in his philosophy of artifacts (Dipert 1993, p. 47). It also has to do with relating the physical nature of an artifact (here: material) to its functional nature. The term 'action knowledge' also suggests a link to action theory. In this paper, a thorough reflection on the consequences of action theory for the nature of technological knowledge does not take place ~~yet~~, but the classification that is proposed here offers an opportunity for that. Vincenti has not made an effort to build such a bridge between his categories and action theory, probably because his interest was primarily of a historical nature and not that of a philosopher.

### 4.5 Other observations

The LOCOS case study shows that the combination of different types of knowledge was crucial in the invention and development of LOCOS. In particular, Kooi's initial recognition of the potential of the LOCOS principle was a rich combination of the four types of knowledge that were identified. That may give us a first clue towards analyzing the idea of knowledge integration (as mentioned at the end of Section 3). Comparison with other case studies where such an integration of knowledge took place, is needed to get more insight into that. In particular, we would need to have case studies that also comprise examples of what Ropohl called 'socio-technical knowledge'. In the LOCOS case that sort of knowledge is not visible. All knowledge we have met was directly related to material properties and what can be done with them. In other words, most of what we have seen deals with the 'material-y-ness' of materials (perhaps this would be a broader alternative to Baird's 'thing-y-ness' of things in which he expressed his concern for the material aspects of technological knowledge).

Another observation, in terms of the knowledge categories in the LOCOS case, is that 'functional nature knowledge' and 'action knowledge' can be transferred from one problem to another. Kooi had gained a lot of knowledge about the surface behavior of silicon when he worked on a silicon variant of the germanium pushed-out-base (p.o.b.) transistor. This p.o.b. transistor was a Philips invention that was made in a period when silicon was not yet used for making transistors. Apart from some more suitable material properties, silicon was more available than the germanium (silicon can be obtained from sand). Kooi's group leader challenged him to work on a silicon version of the p.o.b. transistor. Much of Kooi's knowledge about silicon came from that period of his career. Maybe similar knowledge transfers could have taken place from work that was done by Dr. Feye Meijer in another Nat.Lab. group, which was led by Dr. Sparnaaij. This group was one of the groups that were supposed to do 'fundamental' research. The fact that much later Meijer realized that his measurements of surface properties could have been useful to Kooi, but, at that time, he did not know what went on in Kooi's group[6], shows how artificial and disadvantageous this separation between 'fundamental' and 'applied' research can be when it is used as an organizing principle for an industrial research program. In terms of knowledge management (see the introduction of this paper) the different types of knowledge emerging from those different types of research can be distinguished, but should evidently not always be separated.

## 5. Concluding remarks

This paper is a first effort to use empirical data as a source of inspiration for reflecting on existing perspectives on technological knowledge. A number of already existing insights were confirmed:

- technology cannot be described adequately as applied science,
- different types of technological knowledge can be distinguished,
- defining knowledge as 'justified true belief' is not very appropriate for defining technological knowledge, because it does not do justice to all types of technological knowledge.

In the paper it was suggested to define categories of technological knowledge that relate to current philosophical views on the nature of artifacts and to see how different types of technological knowledge are combined in the research and development work of technologists. Doing so would enable us, in our epistemological reflections, to gain from ideas that have been developed in action theory and philosophical perspectives on the nature of artifacts. This would open new ways to developing philosophical perspectives on technological knowledge. Comparison of the nature of Kooi's knowledge in the LOCOS case with the standard definition of knowledge as 'justified true belief' can be exploited by extending the analysis of knowledge in the LOCOS case to the sources of the various types of knowledge (the 'how they know it' part of Vincenti's analysis). So far we have focused on the content of the knowledge rather than the source of knowledge. As Audi has shown, analyzing the source of beliefs and knowledge can lead to terms such as perceptual, memorial, introspective, a priori, testimonially based, and inferential knowledge. Such terms could be compared to Vincenti's sources of engineering knowledge (transfer from science, invention, theoretical and experimental engineering research, design practice, production and direct trial). Such a comparison could yield further insights into the way technological beliefs emerge and be justified.

## End Notes

[1] The author wants to thank Prof.dr. Anthonie W.M. Meijers for his valuable comments on a draft version of this paper.

[2] This is not a co-incidence. Ropohl’s chapter in the book that Tamir and I edited originally was an invited paper for which we asked him to respond to Vincenti’s book.

[3] An international conference is being planned to be held in Eindhoven, in Summer 2002, to bring together experts from the different perspectives and discuss the nature of technological knowledge.

[4] The explanation is mainly based on Graaff and Kelmans (1966), Munk and Rademakers (1966), and Schmitz (1965).

[5] This section is mainly based on Kooi 1991 and an interview I had with Kooi on April 7, 1998. Technical details can be found in Appels, Kooi, Paffen, Schatorjé and Verkuylen (1970).

[6] Interview with Dr. F. Meijer of December 18, 1997**.**

## References

Appels, J.A., Kooi, E., Paffen, M.M., Schatorjé, J.J.H. and Verkuylen, W.H.C.G. 'Local Oxidation Of Silicon And Its Application In Semiconductor-Device Technology', *Philips Research Reports* Vol. 25. 1970, pp, 118-132.

Audi, R. *Epistemology. A Contemporary Introduction To The Theory Of Knowledge*. London and New York: Routledge, 1998.

Baird, D. 'The Thing-Y-Ness Of Things: Materiality And Spectrochemical Instrumentation, 1937-1955, in: Kroes, P.A. and Meijers, A.W.M. (eds.), *The Empirical Turn in the Philosophy of Technology*. Oxford: Elsevier Science. 2001, pp. 99-118.

Bayazit, N. 'Designing: Design Knowledge, Design Research, Related Sciences', in: Vries, M.J. de, Cross, N.G. and Grant, D.P. (Eds.), *Design Methodology and Relationships with Science*. Dordrecht: Kluwer Academic Publishers. 1993, pp. 121-136.

Constant, E.W. *The Origins Of The Turbjet Revolution*. Baltimore, MD: John Hopkins University Press, 1980.

Cross, N.G. "Designerly Ways Of Knowing: Design Discipline Versus Design Science", Design Issues, Vol. 17, No. 3, pp. 49-55, 2001.

Dasgupta, S. *Technology and Creativity*. Oxford: Oxford University Press, 1996.

Dipert, R.R. *Artifacts, Art Works and Agency*. Philadelphia: Temple University Press, 1993.

Graaff, H.C. de and Kelmans, H. 'The thin-film transistor', *Philips Technical Review*, Vol. 27, No. 7. 1966, 200-206.

Hitt, M.A., Ireland, R.D. and Lee, H. 'Technological learning, knowledge management, firm growth and performance: an introductory essay', *Journal of Engineering and Technology Management*, Vol. 17. 2000, pp. 231-246.

Kooi, E. *The Invention of LOCOS*. New York, NY: The Institute of Electrical and Electronic Engineers, Inc., 1991.

Kroes, P.A, and Meijers, A.W.M. 'Introduction: a discipline in search of its identity', in: Kroes, P.A. and Meijers, A.W.M. (eds.), *The Empirical Turn in the Philosophy of Technology*. Oxford: Elsevier Science. 2000, pp xvii-xxxv.

Laudan, R. 'Introduction', in: Laudan, R. (Ed.), *The Nature of Technological Knowledge. Are Models of Scientific Change Relevant?* Dordrecht: D. Reidel Publ. Comp. 1984, pp. 1-26.

Layton, E.T. 'Technology as knowledge', *Technology & Culture*, Vol. 15. 1974, pp. 31-41.

Meijers, A.W.M. 'The relational ontology of technical artifacts', in: Kroes, P.A. and Meijers, A.W.M. (eds.), *The Empirical Turn in the Philosophy of Technology*. Oxford: Elsevier Science. 2000, pp 81-96.

Mitcham, C. *Thinking Through Technology. The Path Between Engineering and Philosophy*. Chicago: University of Chicago Press, 1994.

Munk, E.C. and Rademakers, A. 'Integrated circuits with evaporated thin films', *Philips Technical Review*, Vol. 27, No. 7. 1966, pp. 182-199.

Ropohl, G. 'Knowledge Types in Technology', in Vries, M.J. de and Tamir, A. (Eds.), *Shaping Concepts of Technology: From Philosophical Perspectives to Mental Images*. Dordrecht: Kluwer Academic Publishers. 1997, pp. 65-72.

Schön, D. *The Reflective Practitioner. How Professionals Think in Action*. New York, NY: Basic Books, 1983.

Schmitz, A. 'Solid circuits', *Philips Technical Review*, Vol. 27, No. 7. 1965, pp. 192-199.

Skolimowki, H. 'The structure of thinking in technology', *Technology & Culture* Vol. 7. 1966, pp. 371-383.

Vincenti, W.G. *What Engineers Know and How They Know It*. Baltimore: John Hopkins Press, 1990.

Vries, M.J. de. *80 Years of Research at Philips. The History of the Philips Natuurkundig Laboratorium, 1914-1994*. Eindhoven: Stichting Historie der Techniek, 2002.

__________. 'Transforming Inventions into Innovations as a Major Concern of the Philips Research Laboratories Management: A Historical Perspective', in Inzelt, A. and Hilton,

J. (Eds.), *Technology Transfer: From Invention to Innovation*. Dordrecht: Kluwer Academic Publishers. 1999, pp. 145-160.