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ORIGINAL ARTICLE

The Structural Characterisation of Risk in the R&D Process of Functional Raw Materials for Electronic Devices

Yoji Chikamori*and Seigo Nasu**
*Kochi University of Technology
**Kochi University of Technology

***Abstract*:** The electronic materials and electronics device industries remain important to Japan in spite of the general decline of the Japanese electronics industry. There is risk and uncertainty when developing functional materials in the electronics industry. However, studies examining the uncertainty and risk variables in the development of functional materials are scarce. This study examines incremental research and development (R&D) developed for raw functional materials for electronics. Our analysis suggests that, as a result of R&D and later industrialisation, the dominant variables are the scientific limits and the uncertainty of the object, an impossible production condition and unknowable marketability.

Keywords: development of functional material, uncertainty and risk, unexpected failure

1. Introduction

1.1 Functional materials for electronic devices

According to the Japan Electronics and Information Technology Industries Association (JEITA) statistics of 2014, the domestic production of the electronics industry in Japan was 11.8 trillion yen. This was a decrease from the 25 trillion yen of 2000. In 2014, the domestic production of the electronic raw materials and electronics device industries were 7.5 trillion yen. The electronic materials and electronics device industries remain important to Japan in spite of the decline in the Japanese electronics industry. The production control and the quality of the electronic components and devices industries are supported by the research and development (R&D) activities of upstream industries. Significant human resources and financial resources are spent on the R&D of electronic raw materials.

From the late 1970s through the early 1990s, in the field of magnetic recording tape, R&D on the magnetic metal particles for the Hi8 videotape was conducted and developed by many raw materials manufacturers in Japan. However, almost all makers ceased R&D before reaching industrial production barring two. These two companies had been founded to study inorganic chemistry and were not specialised makers of magnetic iron oxide. They were unable to take hold in their new market because the market itself did not expand; this was because magnetic recording tape media disappeared due to the digitalisation revolution of recording technology.

1.2 Risk of functional material R&D

R&D for raw functional materials for electronic devices requires sustained attention through difficulties to achieve technological objectives and to reach its goal of realising commercial success. Most of these R&D projects carry a risk that leads to the loss of investment. There is uncertainty and risk associated with the development of functional materials in the electronics industry.

However, studies on uncertainty and risk in the development of functional materials have been insufficient.

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1.3 Objectives

This work examines how an incremental R&D process in the electronic materials industry can be managed. It considers the characteristics and risk variables of an incremental R&D process that leads projects to business success in the electronic raw materials industries.

2. Literature Review and This Study

2.1 R&D management

Niwa (2006) showed the importance of considering R&D management in a high-technology society. That consideration is a core theme in the management of technology, the precise study of which we should focus on promoting. Niwa and Ikeya (2012) studied how management promotes discovery actions in discovery-type research. In discovery-type research, they proposed that there is an importance of the uncertainty of the R&D goal and that there is a limitation on conventional R&D management.

Niwa (2013) supported the necessity for practical and precise study of the management of technology; few studies have examined this research area.

The author has considered uncertainty in the R&D process for functional raw materials for electric devices. From our study, there are four types of risk (Table 2.1) caused by technical hierarchical structures (Figure 2.1) (Chikamori, 2013).

Table2.1 Four Classifications of the State of Risk

Type	Condition	Classification
1	a priori probability	risk
2	statistical probability	risk
3	estimate, judgement	uncertainty
4	unknowable	accident (unpredictable)

See Knight (1921) and Sakai (2012), author postscript.

2.2 The objective of this study

There has been little research based on the specific case of the development of functional materials. Therefore, this is the scientifically least resolved development process, together with its uncertainty and the risk structure of functional materials. In Itaya (2011), discovery-type research was examined, and it was shown that there is high uncertainty in pursuing research goals. However, the success or failure of the business due to the R&D process and the outcome of the development of incremental functional materials are also full of uncertainty. The development and management of the research has a large impact on society as well.

What are the variables that dominantly control outcomes? In this study, we consider the process of incremental development-type research of functional materials on this issue. As a sub-issue, we consider how variables act on outcomes and what differences there are between cases. Furthermore, we divide the business process into two parts: one is the technical development process itself (the below-A stage) and the other follows development (the below-B stage) to the goal. Therefore, in this study, we consider the following questions. What are the risk variables in R&D? Who takes the risk of losing his or her investment in this uncertainty? Is this unexpected or to be expected?

2.3 Academic significance and contribution

This study contributes to the deepening of practical research on unresolved elements of the management of R&D in technology business administration. In addition, clear discussion has been lacking on the technical development process, business processes following development goals and other development. This study examines uncertainty and risk structure in incremental development-type research on functional materials. Thus, this discussion contributes to the advancement of technology management of practical research. For the purposes of this study, risk has a broad meaning: risk includes risk, which one can evaluate using probability, and uncertainty, which is impossible to evaluate (Sakai, 2012). Here, risk does not incorporate results.

3. Case Study

3.1 Method

We examine the development of certain functional materials to organise the event, which is divided into the development process and the commercialisation process of the setting up of technology goals for the developed material. We consider uncertainty and risk structure. In the analysis, objective public information is used, including facts about development that I encountered during my work, and information, patents and papers obtained in activities related to development. We use public information for the case of the dye for a plasma display panel (PDP) and the dye for a liquid crystal display.

The central data is the 8 mm video for the metal magnetic powder and parts for the lithium-ion battery. The recording device has a magnetic tape that is a component of the functional expression of magnetic powder and the technological hierarchy of the magnetic recording system using magnetic tape (Figure 3.1). For lithium-ion batteries, cathode material, anode material, an electrolyte solution and the separator are the four main parts that make up the battery (Figure 3.2). Furthermore, the battery can be further incorporated into a higher-level system. The ultrafine titanium oxide used in sunscreens has a similar hierarchy. It is also comparable with the two cases of development (Table3.1), as verified inference.

3.2 Case 1: Metallic magnetic powder

3.2.1 The state of magnetic recording media in 1980

In 1980, the theme of development shifted to metallic powder from γ iron oxide magnetic powder. At that time, video began to spread rapidly, with the growth of the VHS system. Morita, the Chairman of Sony, proposed the development of a high-density magnetic recording medium in 1977, and the development of 8 mm video began.

Five companies jointly proposed the basic idea of the new format proposal for 8 mm video in 1982. The development of metal magnetic powder for 8 mm video was started earlier by many material companies. Metal tape for audio was released in 1978. Metallic magnetic powder is an industrial material produced using a process similar to that for producing magnetic iron oxide, a chemically synthesised goethite obtained by crystal growth in an aqueous solution as a starting material. A metallic iron obtained by hydrogen reduction into a needle-like shape was its main component.

3.2.2 Situation of the material industry at that time

According to the sales department of T company and industry newspapers, over 40 competitors entered the metal magnetic powder market, as shown in Table3.2.

3.2.3 History of the development of metal magnetic powder in T company

Beginning with audio use

Around 1976, when the metal tape was proposed, T company was manufacturing titanium oxide and magnetic iron oxide as the two pillars of its business. For T company, the demand and information related to the production and supply of the magnetic powder that showed the promise of metal tape as a next-generation magnetic recording medium were presented by the parties concerned. As a leading manufacturer in the field, T company decided to develop metal magnetic powder with a desire to occupy the metal magnetic powder market.

From audio to 8 mm video

During 1978–1982, we were developing magnetic powder for metal audio tape. We found that the technology to make metal powder was very different from that used to make magnetic iron oxide. Experimental data were examined day by day. Customer companies conducted the same machine test that tape manufacturers do. It requires the support of mass production facilities. The installation of both pilot-scale equipment and commercial production facilities was necessary. However, the lack of information on feasibility and the uncertainty regarding the economic performance halted decision making on investment.

It was thought to require considerable time to accumulate information to create mass production facilities, and 8 mm video became an attractive object from around 1981. In February 1982, the object was changed to 8 mm video because of the larger market expected for it.

Table3.3 shows important actions or events in T company organised to correspond with key trends in the 8 mm video system.

3.2.4 Difficulties in technology development

Scaling problems

Needle-like goethite is extremely sensitive to the partial pressure of water vapour in the vicinity of a particle. There was greater uncertainty for the engineering design of the large furnace to work it in. For example, the difficulty of reducing operational unpredictability comes from powder behaviours such as adhesion. Metal magnetic powder is unstable by nature, so it is suddenly heated by small vibrations or contact in the air. This problem remained until the final stage.

Challenge of 0.1 μm

We began development of the 8 mm video with a target of a 0.4 μm particle size in August 1982. However, according to Hitachi Maxell (MX) and Sony (SMP), the particle size required was 0.2 μm. This was reported in July 1983 through the sales department and the trading company.

We began working to develop for 0.2 μm metal objects, studying the manufacturing conditions of goethite. Information was obtained that its size was at approximately 0.1 μm. Then we found that MX and SMP had changed their requirements to 0.1 μm. Figure 3.3 shows that all functional metal powder properties are determined by the properties of the synthesised goethite as a starting material. It became necessary to return manufacturing conditions to goethite each time the target changed.

For the 0.1 μm particle, we worked towards a solution to balance sintering to the adjustment of the coercive force and the opposite direction, anti-sintering, to improve dispersionability and orientation. I had no ideas apart from that solution. It worried me for a long time.

For the 0.1 μm particle, we were working, exploring many techniques to balance all other characteristics, until 1988.

There were 9,552 patent applications that were related to the 8 mm video. Among these, 1,399 concerned metal magnetic powder. We examined these 1,399 documents in this study. We show a typical patent application example from the technical point of view of the device in Table3.4. A particle size of less than 0.3 μm and a large specific surface area are the important characteristics. Evidence indicates a trend in technology around the 1980s of the synthesis of very fine particles. This is the most important element for high recording density and noise reduction.

Recognition of limits, particle length of 0.2 μm

In the deadlock mentioned above, projects came when T company received the transfer of a plant from A company in 1988, including their technical data. A company had been promoting technological development and the commercialisation of metal magnetic powder. Information on them was subject to the disclosure of A's data. A's experimental data showed that objects it had fabricated of 0.1 μm were exceeding the limit at that time. We were determined to prepare a sample for an important customer at 0.2 μm. However, a decision was taken to abandon the development and investment in 1992; although major customers recommended continuing development, we withdrew in 1993.

The plan was foreordained to fail

Metal magnetic powder has serious defects. First, it is not stable in air. Abrupt temperature increases suddenly oxidises it because of its high specific surface area. Second, it requires a vast amount of energy during the manufacturing process. Third, it is very difficult to control its properties. Magnetic properties are controlled by the shape of the metallic particle that remains after reducing the oxide particle. Therefore, magnetic properties have very large variations due to their process history. By contrast, in magnetic iron oxide, a variety of features can be controlled. Moreover, being an oxide, it is basically a stable material.

Therefore, the metal magnetic powder engineered was an unsatisfactory material. It was fated to fail from the time the theme was set. It was found that there was a contradiction in the concept of an ultrafine metal magnetic material for use in high-density magnetic recording.

3.3 Case 2: Lithium-ion battery

3.3.1 LiB technology currently

A lithium-ion secondary battery using carbon materials instead of a metal Li as the negative electrode (LiB) was proposed by Akira Yoshino in 1985. Sony began industrial production in 1991 after further study. The use of LiB steadily developed. LiB was a major material, cathode material, anode material, separator and electrolyte. Unlike other battery systems, the selection of these materials is wide and the characteristics of the chosen material system may vary significantly.

For drastically improved performance, at present, an intense development race is being carried out on a large scale. The structure of the battery and related industries are very complex; it is not possible to analyse much in this study. We examined the risk variables in the nonwoven separator (Example 3) and the anode material (Case 4), these being materials known to the authors.

3.3.2 The current market in LiB

The engineering structure with the four major materials, as can be seen from Figure 3.2, has the same structure as the metal magnetic powder (magnetic media). However, unlike metal magnetic powder can be various combinations of materials (Kanemura, 2010), (Yoshino, 2003), a (Ogumi, 2008). Therefore, despite being unforeseen, because competition has not settled, the chance has not been lost. It is a development object worth challenging for its market potential.

3.4 Comparison between LiB and metal magnetic powder

3.4.1 Same structure

LTO and nonwoven separator have the same hierarchical structure and variables.

3.4.2 Differences

An important difference is whether or not it is possible to use existing production facilities. In the manufacture of LTO or nonwoven fabric separators, it is possible to use existing equipment. Because an initial investment was required, there was no investment risk up to the stage of commercialised line construction. However, for metal magnetic powder, it was necessary to make new designs. Moreover, it was difficult to predict what equipment would help. Since there was a large difference in the responsiveness of the sample supply, there were restrictions in the case of the sample activities of the metal magnetic powder. Because of this large difference, the equipment factor was determined as a dominant variable.

For LiB, it should be noted that it can occur in a variety of combinations (Ogumi, 2008; Kanamura 2010). Therefore, it is possible to change the evolution of the battery complex even as the inferior remains largely likely to be predominantly used. It is necessary for it to continue running in parallel business and development. It is a painful, long-distance competition, but it is worth it to continue. By contrast, in the case of metal magnetic powder, it was difficult to redeem a poor performer once adopted, even if the evolution of standards and equipment occurred synergistically; also, small market was delayed. Only Sony played a leading role in the tape field, with a few main companies like Fuji, Hitachi Maxell and TDK.

3.5 In addition to other cases

The following three cases are investigated and compared in conjunction with six other cases. We consider these six cases in Section 4.

Case 4: Sunscreen cosmetics (T company)

Case 5: Organic pigment for liquid crystal panel for colour filter (DIC)

Case 6: Near-infrared-absorbing dye in plasma display for members (Japan Carlit)

4. Results and Discussion

4.1 Main risk variables and level setting

In Section 2.2, the authors put forward three questions. The first one is below.

Question 1: What are the risk variables in R&D?

(1) We showed that in the process of development of functional materials, it is possible to set the same structure and the same risk variables. The level of the dominant variable is different in each case.

We examined several cases of functional materials development. We organised each event, so we could discuss the risk variables separately as A-stage and B-stage. In Table4.1, taking the independent variables (cause variables) in the incident cases, we tried to distinguish the four levels. This was then applied at a level judged to be true for each case.

As was described in detail in Case 1 of the metal magnetic powder, the variables that determine the success or failure in the A-stage are stability as a substance, the use of existing facilities and the stability of the targets. These three factors show their effectiveness in achieving their object. Metal magnetic powder is chemically very unstable. There is uncertainty in handling its unpredictable nature like the sudden oxidation reaction that happens during handling in air. By contrast, LTO and the nonwoven fabric separator are very stable as materials, so there are no handling problems. When you apply this knowledge to Cases 2 and 3, the level of variables related to chemical stability is positioned very low.

By comparing on the basis of the metal magnetic powder, it is possible to determine the variable on one of four levels. For judging these four levels, we use the four risk categories from previous research to create Table1.1. Applying this classification to other factors, we obtain Table4.1.

4.2 Consideration of the development-type research process called the A-stage

(1) Uncertainty and the burden of investment risk

The second question from Section 2.2 is below.

Question 2: Who takes the risk of losing his or her investment in this uncertainty?
As in the case of the magnetic recording tape and the lithium-ion battery, the hierarchical structure between the companies is caused by the technical hierarchical structure, and functional materials-based companies are forced to assume the investment risk and uncertainty about the outcome of product development. If the characteristics of the request are complicated, many entrants into business-to-business relationships will be uncertain; to strengthen the relationship between particular organisations, participation in consortiums will be useful to obtain information and risk reduction of information.

Our study demonstrates that in a hierarchical structure between companies caused by a technological hierarchical complex, functional materials companies assume the investment risk and uncertainty of the outcome in product development. When inter-organisational relationships are complex and the required characteristics are uncertain, a consortium is desirable. Such a structure is useful for obtaining information and reducing risks by enhancing the relationship with the particular organisation. It has been argued that device companies can get technical information and comprehend technical maps by collecting a variety of samples from material companies and by evaluating them. Therefore, they can decide the directionality of technology development with low cost and low risk.
(2) No one can know what the material constitution of the lithium-ion battery will be in the future

From the case of the lithium-ion battery, with respect to decision making, the uncertainty of the battery configuration and the uncertainty of the target characteristics, such as the fluidity of industry inter-organisational relationships, are impossible to predict. Thus, unpredictability is noted as a fourth risk.

4.3 Consideration of the commercialised stage termed the B-stage and its goal

In Section 2.2, the authors put forward three questions. The third one is below.
Question 3: Is this unexpected or to be expected?
In the passage from the theme setting to the goal, the object must be achieved and the goal must be achieved as expected. We show that in the face of scientific limitations, such as in the case of the metal magnetic powder, it is ignorant to evaluate the post at the time of decision making. Case 5, the liquid crystal panel for organic pigments, and Case 6, adding PDP for near-infrared-absorbing dye, are combined with the four cases in Table4.2. This has its result in the B-stage commercialisation.

In the field of the functional material industry, small business management often sets a plan for development that corresponds with the needs of their customers. In the functional material industry field, small business management often sets a plan for development in a manner that corresponds to the requests of customers. For small businesses, their resources are limited and weak, and it is important to make steady progress and achieve even small goals. Theme setting is a decisive element of the outcome. Thus, in theme setting, Table4.1 shows that these aspects must be considered: Aspect 1: scientific limit and uncertainty of the object and Aspect 2: validity of manufacturing conditions and equipment.

5. Conclusion

We showed that the dominant variables for the R&D of functional materials and subsequent commercialisation are (1) the scientific limit of the target, (2) the accumulated resources of the company, (3) the technical elements that cannot be known before the start of development and (4) the uncertainty of the target market.

6. Further Study

In future work, we will investigate cases of technology management for functional materials industries affected by unpredictable factors and compare them with general purpose materials. Then, we will consider technology management for functional materials with uncertainty.

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Table3.1 Elements of Devices in the Case Studies

Device	8 mm video tape	Lithium-ion battery	Sunscreen cosmetics
use	recording for Hi8	cell for module	UV cosmetics
product	only in a Hi8 system	many types	many types
standard	single standard	variety of standards	law and standards consumer safety
element 1	magnetic powder, as Case 1	separator nonwoven, as Case	inorganic UV filters titanium dioxide, as

		2	Case 4
element 2	resin for coating-layered film	negative electrode LTO as Case 3	organic UV filters
element 3	binder	positive electrode	oily ingredient
element 4	base film	electrolyte	surfactant
other	other materials	other materials	other ingredients

Table3.2 Major Companies That Entered Metal Magnetic Powder Development

Industry classification	Companies	Motivation for entry
magnetic iron oxide	Titan-kogyo Toda-kogyo	to be the leading company in a new generation of magnetic material
titanium dioxide	Ishihara-sangyo Sakai-kagaku	deployment of powder technology
inorganic chemistry	Dowa-kogyo Kantodenka-kogyo Tone-sangyo	iron powder manufacturing resources similar technology
functional chemistry	Nissan-kagaku Nikkorika	resources new business
big chemical	Mituitoatu-kagaku Tosoh, Kao	resources resources
iron and steel	Nippon steel	iron making
non-ferrous metal	Furukawa-kogyo	metal

Table3.3 Development History of T Company from 1978 to 1993

	Time and action
Ⅰ	first stage, 1978 to 1982
	development of magnetic metal powder for audio tape object: high orientation ratio and high residual magnetic flux density, study of basic data accumulation and study of reduction furnace format
Ⅱ	second stage, 1982 to 1985
	development of magnetic metal powder for metal video tape object: high performance material for highest recording density, very fine particle, highest dispersion ability and length of particle of 0.2 μm and 0.1 μm in 1982, the 8 mm video conference was established in 1985, Sony presented CCD-V8
Ⅲ	third stage, 1986 to 1988
	development was stalemated, goals that could not be reached object: length of particle of 0.1 μm, high SSA, high σs, very stable property and high dispersion ability
Ⅳ	fourth stage, 1988 to 1992
	exchange of views with S company established manufacturing process at pilot plant for a particle length of 0.2 μm ☆1989, Sony presented 'Hi8ME', a material evaporated on film ☆1989, Sony presented 'Hi8MP', which is coated very fine
Ⅴ	final stage, 1992 to 1993
	withdrawal from metal magnetic powder development

Table3.4 Examples of early 1980s Patents Related to Particle Size

publication number	applicant	date of filing	date of publication of application	particle size length or SSA	top inventor
S58-053022	Maxell	24.9.1981	29.3.1983	L < 0.3μm	F. Togawa
S58-070426	Sony	21.10.1981	26.4.1983	SSA > 45 m^2/g	Y. Cyuubachi
S58-119609	Fuji	11.1.1982	16.7.1983	70 m^2/g	H. Miyaduka

Table4.1 Estimated Level of Variables with Risk in the R&D Process of Functional Materials

				estimated level of variables			
				case1	case2	case3	case4
	elements	symbol	variables	metal powder	separator for LiB	LTO	TiO2 from cosmetics
elements of development process (A-stage)	difficulty of R&D	**a1**	**☆stability of substance**	**3**	**1**	**1**	**1**
		a2	scientific basis	3	1	1	1
		a3	difficulty of property control	3	1	1	1
		a4	amount of work required for data collection	4	3	3	1
		a5	cost for data collection	4	3	3	1
	investment burden of manufacturing equipment, etc.	**b1**	**☆availability of existing facilities**	**3**	**1**	**1**	**1**
		b2	pilot plant	4	1	1	1
		b3	commercial plant	4	1	1	1
	manufacturing cost	c1	manufacturing process	3	1	1	1
		c2	raw material cost for synthesis	3	1	1	1
		c3	utility cost	3	1	1	1
	standards	d1	standards	3	2	2	1
	object	e1	interviews with customers	3	3	3	2
	object	f1	☆stability and reliability of objects	3	2	2	1
	relation with other	**g1**	**☆information collection from customers**	**3**	**3**	**3**	**1**
	universal use	h1	versatility of	3	2	2	1

			applications				
elements in B-stage	market elements to goal	m1	switching risk to competitors' material	3	3	3	2
		m2	**☆appearance risk of new technology**	**4**	**3**	**3**	**1**
		m3	**☆disappearance risk of final product**	**4**	**3**	**3**	**1**

Table4.2 R&D Results by the Final Market

	Case 1	Case2	Case 3	Case 4	Case 5	Case 6
functional material	metal powder	Nonwoven separator	LTO	ultrafine TiO2	dye	dye
device	Hi8 tape	LiB	LiB	UV filter	liquid panel	plasma display
decision risk level	4	3	3	1	3	1
material company	T	N	T	T	DIC	Japan Carlit
R&D result	dissatisfaction	improvement necessary	improvement necessary	achieved	achieved	achieved
action for commercialisation	not	achieved	achieved	achieved	achieved	achieved
final market	bad	uncertain	uncertain	very good	very good	disappeared

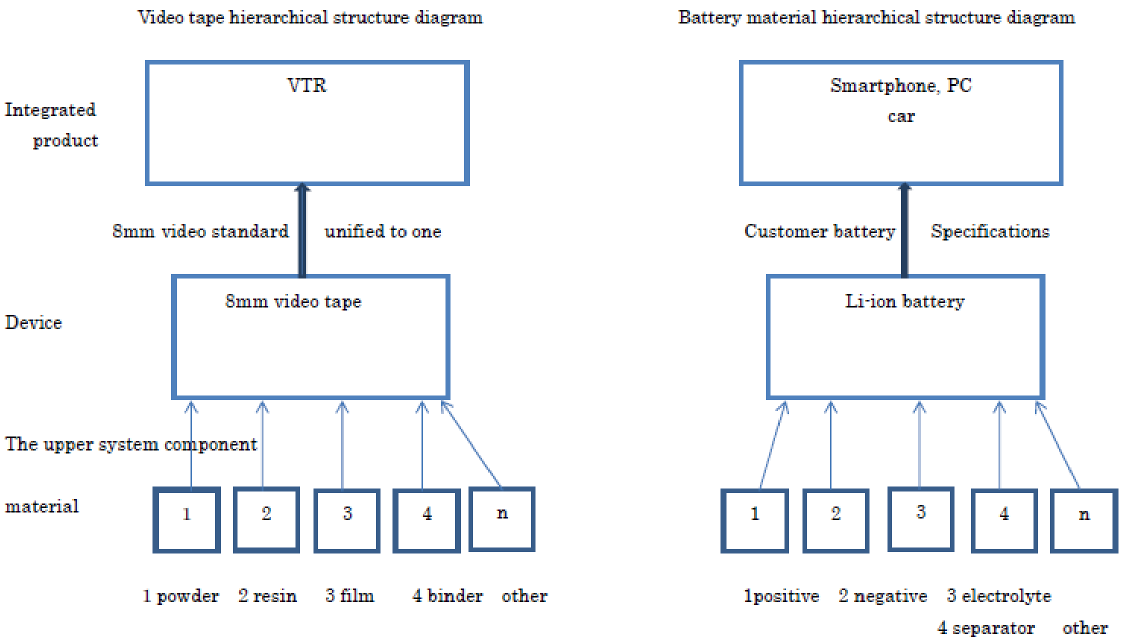

Figure 2.1 Diagram of the Hierarchical Structure of Devices

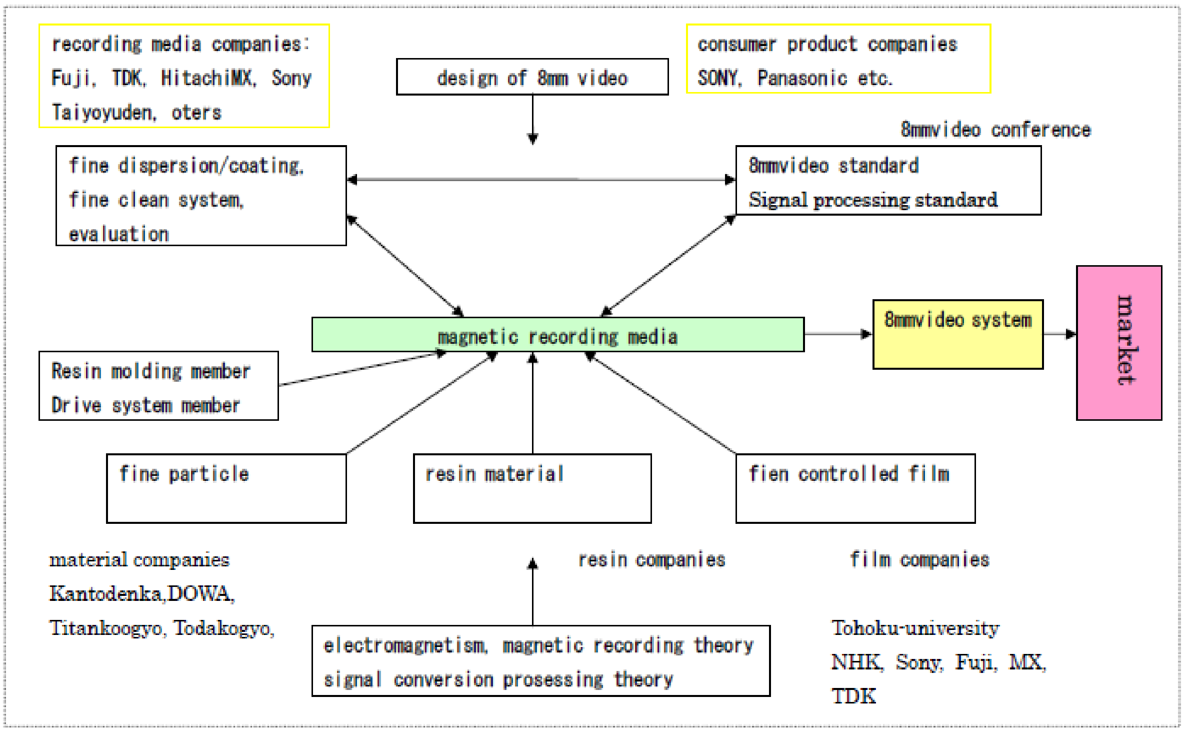

Figure 3.1 Engineering Elements in Recording Media

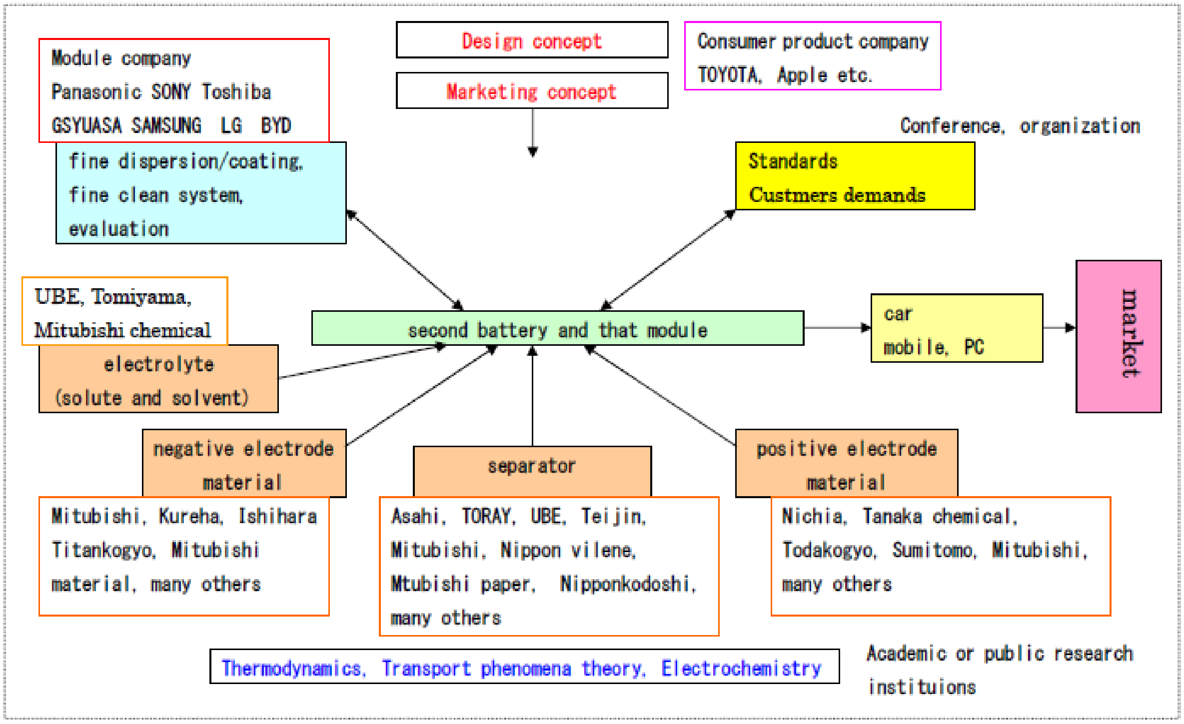

Figure 3.2 Engineering Elements in the Li-ion Battery

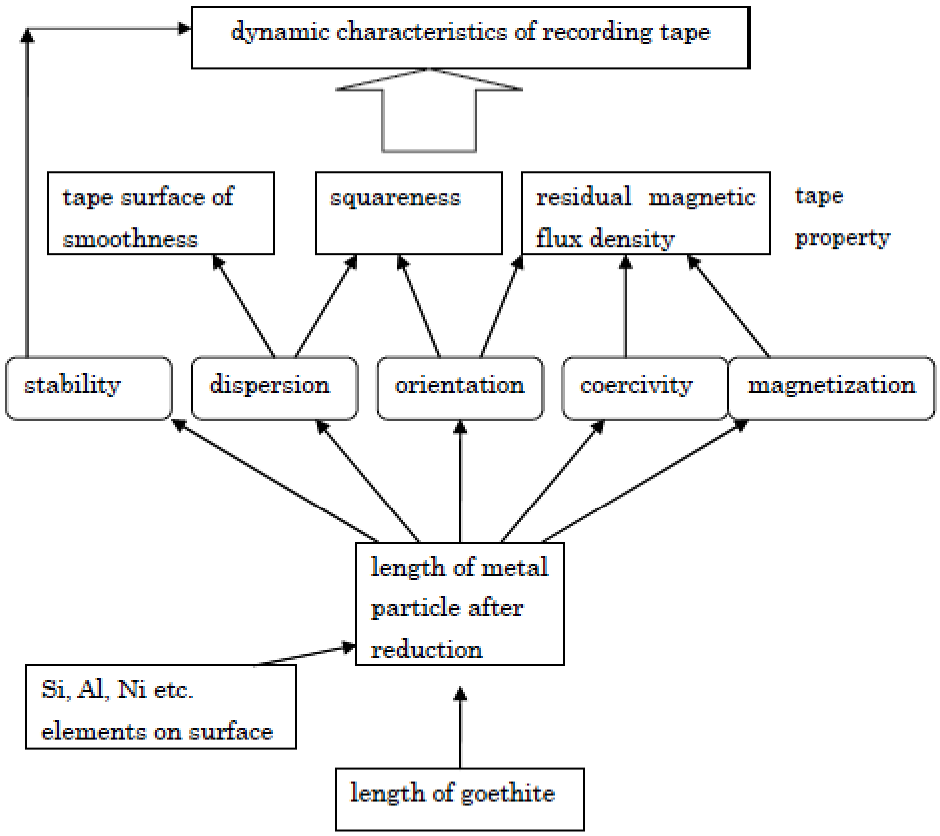

Figure 3.3 Relation between Goethite and Tape Properties