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Ecomaterials toward Sustainable Society

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The current status of the research and development of ecomaterials is described. The concept of ecomaterials has been proposed in early 90th, and it is distributing by connecting with Eco-design and Life-cycle designing. The progress of the concept and the development on Ecomaterials through five meetings of International Ecomaterials Conference and related symposiums and workshops are highlighted.

Keywords : Ecomaterial, Life-Cycle Design, recycling, resource productivity, hazardous substances

1. INTRODUCTION

At spring of 2003 Japan government has set qualitatative target on material flow in Japan toward 2010. Namely, Promoting resource productivity 1.4 times, from ¥280,000/t to ¥390,000/t. Promoting the ratio of circulation from 10% to 14%. Reducing final disposal of waste, from 56Mt/y into half. This setting of target means Japan government has started the effort to control material flow in Japan. 2,400 million-t resources per year are consumed in Japan. Beyond them hidden material flow is risen by importing raw materials.

Table1 numerical aim of master plan for sound material-cycle society

MASTER PLAN for SOUND MATERIAL-CYCLE SOCIETY From 2000 To 2010

Input	Resource Productivity = GDP / Total Resource Requirement	280,000¥/t ↓ 390,000¥/t
Circulation	Recycling rate = Recycled resource / (Recycled resource + Natural Resource)	10% ↓ 14%
Output	Final Disposal of Waste	56 Mt ↓ 28 Mt

Halada estimated the fundamental data of TMR(Total Materials Requirement) for metallic ores[1] in 2001. Fig.1 shows the TMR of each metal. About 3 billion tons per year of natural resources are moved with causing by the consumption of iron. Gold is the king who moves greatest amount of natural resources, while its consumption is less than 3k tons. Totally, about 20Gt of resources are consumed per year to obtain metals in the world. Generally speaking, rare metals and noble metals, which are used in the various part of industry such as catalysis and devices, have greater hidden flows to cause various environmental impacts. The other environmental problem regarding substances and materials are is the problem of pico-grams, attach of various toxic substances. New substances are taken out or human beings have produced while increasing the quantity of production. The case where it has had a bad influence on earth environment or the human body,

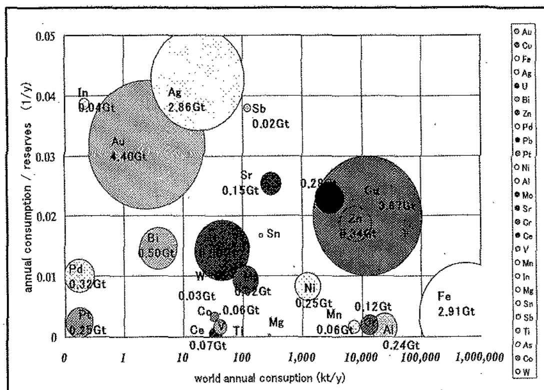

Fig1.TMR of metals

Metals are plotted by world annual consumption on x-axis. Y-axis is the consumption ratio of resources. TMR is presented by the area of the circle

without the ability of them fully managing is reported well. Materials technology is trapped in a pincer drive between the problem of Giga tons, namely, the huge quantity of materials currently used.

2. KEY CONCEPT of ECOMARERIALs

The roles of materials for the environment is arranged in the earlier paper.[3]. Materials for the environment were classified into two types as "Functional materials for environmental protection", "Materials for advanced energy systems" and "Materials for life-cycle design for

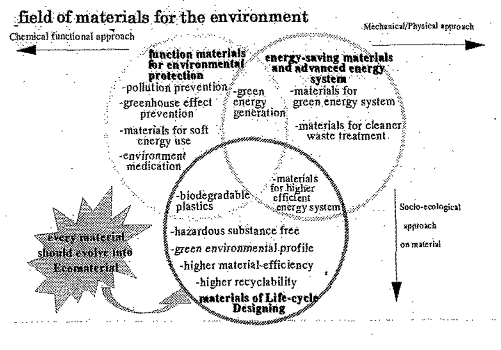

Fig.2 three types of materials for the environment

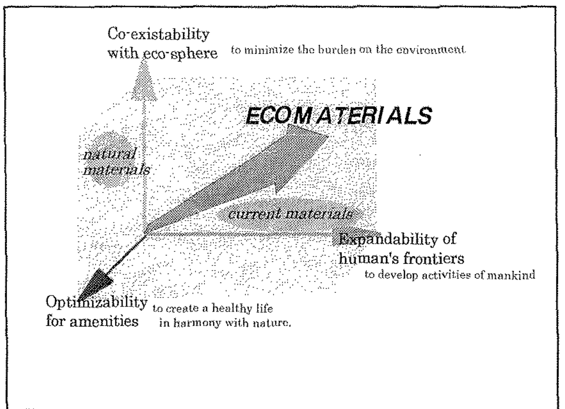

Fig.3 Ecomaterials as the development of materails which follows a holistic view of three strends

environment" shown as Fig.2. The last type of materials are called "ecomaterials" in the strict sense of environmentally couscous and benign materials. The concept of Ecomaterials was proposed [2] at the early 1990s. At the first stage of the developing Ecomaterial, three indices (Fig.3) of ecomaterials was pointed out.

1) Expanding human frontiers: activities of mankind in development.

2) Co-existance with the eco-sphere: to minimize harmful impact upon the environment.

3) Optimizing amenities: to create a comfortable life in symbiosis with nature.

These indices are used to explain the ecomaterials not as special ones with some peculiar characters or functions, but that all materials should evolve into ecomaterial.

For life-cycle design type of ecomaterials, the utilization type of the material should be considered. Such as consumer materials which are consumed daily with their useful functions of materials itself, commodity materials, which are mainly used in industry on the basis of contractual purposes or as in the infrastructures, and materials for power transmission media which are materials used in machines and automobiles. Halada and Yamamoto[3] categorized these materials for the environment into 4types of materials, namely "Materials with less hazardous substances", "materials with greener environmental profiles", "Materials of higher recyclability" and "Materials of higher resource productivity". (Fig.4) The concrete exsample of ecomaterials are reviewed by Halada [4].

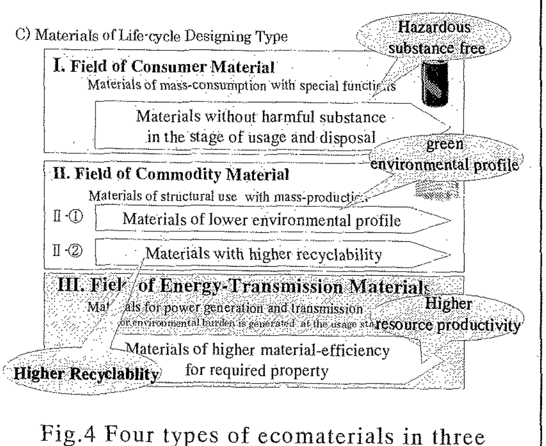

Fig.4 Four types of ecomaterials in three material usages

3. DEVELOPMENT of the CONCEPT of ECOMATERIALS

The International Conferences of Ecomaterials have been held since 1993. This meting is the 6th meeting of the International conference of Ecomaterials. The meeting have been taken the role to develop the research & development and also the concept of ecomaterials.

Table2 Progress of ecomaterials conference

-- International Conferences on Ecomaterials

1993/8 First Ecomaterials Conference (Tokyo) 185papers
Materials Design for Environment 8, LCA 6, Waste and Recovery 5, Recycling 19, CO2 10, Fleon and Sox 4, Bio-plastic 9, Ecomaterials for automobiles 6, New materials 10, Bio-technolgy 3, and posters

1995/9 2nd Intnl. Conf. on Ecomaterials (Xi'an, China) 222 papers
Agriculture & Ecomaterials 38; Transportation, Energy, Resources & Ecomaterials 41; Recycle and Reuse of Materials 34; Recydable Materials Design 12; Environment Friendly materials 4, Environment Pollution preventing materials 77; LCA and Ecobalance 12;

1997/9 3rd Intnl. Conf. on Ecomaterials (Tsukuba Japan) 219 papers
Design of Recyclable Metallic Materials 6; Bio-compatible materials & Ceramics 7; Eco-product 11; Metal recycle 14; Material for Environmental protection 11; Plastic Recycle 14; LCA 17; Advanced material-processing 8; Biodegradable materials 5; Wood-based materials 5; Building Structure materials and renewable sources 11;

1999/11 4th Intnl. Conf. on Ecomaterials (Gifu Japan) 192 papers
Design of Recyclable Metallic Materials 12; Eco-product 12; Metal recycle 8; Material for Environmental protection 21; Plastic Recycle 9; LCA 8; Advanced material-processing 11; Design of plastic for environment 5; Wood-based materials 5; Building Structure materials 10;

2001/10 5th Intnl. Conf. on Ecomaterials (Hawaii USA) 151papers
and 1st-4th Int.Conf. on EcoBalance since 1994 to 2000.

The categorization of ecomaterials into 4 types was developed by Eco-efficiency consideration through life-cycle[5]. Eco-efficiency(EE) consideration gives the relation;

$$EE = \frac{\text{service}}{\text{life-cycle environmental burden}} \qquad (1)$$

The life-cycle environmental burden is schematically shown in Fig.5, and divided into four environmental burdens in each stage of life-cycle:

b_P: the burden in production,

b_U: the burden through usage,

b_E: the burden of End-of-Life,

$(-b_R)$: the deduction of burden by recycling.

The four types of ecomaterials are corresponding of these burdens; namely, materials of greener environmental profile mainly reduce the burden in production, materials of higher resource productivity mainly reduce the burden through usage, materials less

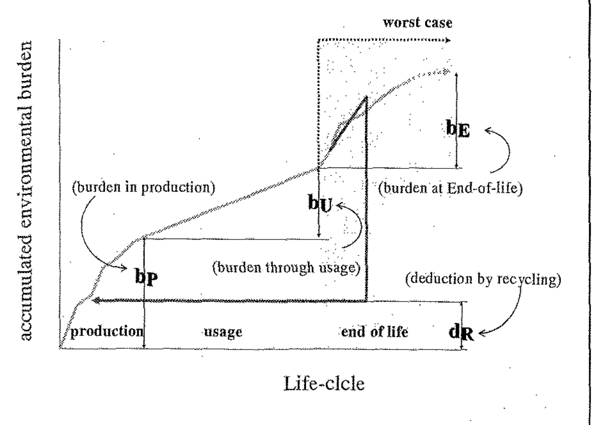

Fig.5 environmental burden of material through life-cycle hazardous substances mainly reduce the burden of End-of-Life, and materials of higher recyclability improve the deduction of burden by recycling.

While the life-cycle consideration puts the viewpoint on each product, the discussion of sustainability gives more wide aspects on the role and problem of material and its usage. New progress of the discussion of sustainability related on materials technology has started E-MRS at 2002, named MATAFORUM. MATFORUM2002 proposed the following materials declaration. This summarizes recommendations for the goals for research, development and implementation of novel materials and processes.

MATFORUM2002
For sustainable product realization, materials, their supply and process chains, production, utilization and consumption must address the three pillars of sustainability: economy, ecology and society Consequently every single step in materials flows, including exploration, mining, production, distribution, utilization and recycling must not only fulfill the "usual" functional and economic requirements but must also meet the ecological and social demands of sustainability. In order to achieve sustainable product realization, the materials research community must consider the following factors: - Integration of environmentally benign design, materials, and manufacturing over all stages of the life-cycle - Exploration and mining of raw materials respecting socio-economic standards and preserving the eco-sphere - Optional exploitation of raw materials and natural resources including synergetic utilization of by-products - Energy efficient production technologies and product distribution, if possible based on regenerative energy sources - Minimal harmful effects caused by the emission of secondary products - Durability, recyclability and closed loops - Traceable and accountable waste management - Appropriate information and education of the stakeholders in the materials and products These issues represent general principles for the implementation of sustainable materials, products and processes. Augsburg, September 19, 2002 On behalf of the participants:

4. LATEST DEVELOPMENT of ECOMATERIALS

The development of ecomaterials are already reviewed in literature [3]-[5]. The latest developments and new comers of ecomaterials are introduced in this paper. They are introduced following the classification of four types of ecomaterials.

4.1 Materials less hazardous substances

Materials of less hazardous substances are rapidly developing in the area of household electronic equipments and the parts of automobiles, according to the regulations such as EU dictative of WEEE and Rohds.

Typical examples
- Pb-free solder - Pb-freemachining steel - Cr-free surface-treated steel - Plastics without harmful fire retardant - Hg-free dry cell
New approarches
- Hg-free lamp - Pb-free Brass - Pb-free Piezo electric ceramic - Eco-semiconductor GaAs→ β FeSi2

Marcury-free Xe flat discharge fluorescent lamps are being developed for LCD backlights and litings[6]. The lamps have a simple structure with insulated electorodes and operated with an ac pulse voltage..While Arsenic in GaAs is very toxical substance and verious semiconductors use heavy chemical elements such as Cd, Se, As, environmental semiconductors are being developed[7]. The typical environmental semiconductors are Si compaounds or silisides such as β-FeSi2(beta iron-di-silicide), Mg2Si and Ca2Si which are consisting of extremely abundant chemical element like Si, Fe, Mg and Ca in the earth's crust. They are expected as the third generation of semiconductor following silicon semiconductor abd GaAs semiconductor. However, as their crystal structure is very complicated, the further development is required to handle higher metlting point materials and to controle their micro-structure. Alternate Pb from various components are in progress in every area of products. Not only ferrous-machining steel but also non-freeous metals such as bearing materials are at the target of Pb-free such as Pb-free brass. When Pb is an important element of the naimed phenomenon, it is difficult to altenate it. The case of PZT was the typical one. However, Pb-free piezo electric ceramic has been investigated and developed. Regarding to the development of Pb-free solders, the phase of research is changing from recovering the optimum conposition into investigating properties, stabilitises and processing.

4.2 Materials of green environmental profile

Materials of green environmental profile are materials with small environmental load from resources mining to material manufacturing. Therefore they can be divided into two types of materials. One is the materials of greener resources. The others are the materials produced and treated by greener processes. Newly developed ecomaterials are mainly belonged to the latter group, relating with the development of LCA and Green Chemistry.

Typical examples

materials from renewable resources
phyto-plastics, wood based materials,
wood ceramics, soil ceramics
materials from waste (resources inside techno-sphere)
cement from municipal waste (ex. eco-cement)
cement from ash
various new material from waste
Material From Coal Slurry
Ceramic from aluminum slurry
Composite from recycled plastic multi-layer fiber
materials processed with less emission and energy consumption

New approaches

Light metals with less input of process energy
Catalyst for soft reaction
Green plastic
Lignin-based materials
Various cascade-recycled material
materials from lower TMR resources

Cho et.al estimated the energy requirement of production of Cu wire to make the process selection of wiring.[8]. T.Raja et.al. reported the environmental benign catalyst for organic transformations.[9] It can make smooth and lower-energy consumption reaction by palladium catalysts on modified mesoporous materials in green chemical processes and expected as the versatile for many transition metal catalyses in organic synthesis. In the field of bio-based materials, biomass derivered plastics with bio-degradablilty are developing with naming themm as green plastics. As a biomass derived composite, lignin based composite is on investigation. Many recycled materials mainly from waste plastic are proposed according with the progress for recycing-based society. Alternation of novel element from functional material is also a new trend of ecomaterials approarch. Ni-free Cu alloys were developed by Yoshimura et.al[10] Pd-less membran for hydrogen purificator was developed by Zang et.al [11]. These approarches are expected to reduce the total material requirements.

3.3 Recyclable materials

Higher recyclablity is another keyword of ecomaterials. The issues on recycling are usually supposed as the problem of collecting system or of recycling process. Recently, DfE(design for environment) has roused the importance of the product design to ease the recycling. Materials-design has also similar problem, because almost all materials are used as macro-composite, such as surface treatment, addition of second element, painting, joining and so on. The recyclable design is also important in the field of materials

Typical examples

recyclable designed alloys
steels with less number of elements
common aluminum alloy
alloys robust for impurities
recyclable designed plastics
recyclable designed composite
decomposable composite
composite of same family of material
materials for easy disassembling

New approaches
Closed recyclable plastic
Utilization of impurity as an element
Upgrade recycle
Recyclable FRP with disassembility

The most important progress of materials with higher recyclability is the development of plastics with closed-loop recycling. As PET bottles are increasingly consumed as more than 10 million tons of PET resin is estimated to be used for PET bottles in 2006, we need to establish the closed loop of recycling PET. A new technology, named AIES process was developed to enable closed loop recycling PET bottles. High purity BHET(bis-2-hydroxyethel terephthalate) can be obtained by purification process without proceeding the depolymerization down to such starting substances of PET resin synthesis as TPA or DMT and ethyle glycol.[12]. In the field of metals, problem of degrading by impurities which are mixed in technoshere are nearly on solution. Owasa et.al succeeded the active utilization of Cu which is contained in iron scrap as impurity called tramp element.[13]. Further innovation has been achieved in the field of Mg-alloy recycling. Solid tips of Mg scrap are treated by extrusion process to produce bars with fine grain size. In this process properties of strength and ductility are simultaneously improved, so that the process ids called "up-grade recycling"..In the field of composite many trials to improve recycrability are investigated. Fukushima mentioned the recyclable design of Fiber reinforced concrete for building useage[14]. These investigations have been subjected in a national research project named "Barrier-free processing for design for the environment"

3.4 Materials of higher material efficiency

Typical examples
materials with higher performance in the usage stage
high-strength steels for automobile
heat resistant alloy for high temperature turbine
light weight alloys for vehicle
Al alloys for automobile, Mg alloys
higher reliablity long life material
Factor 4 steel (ultra steel)
good formability material
by Powder Metallurgical technolog
other materials designed for LCA oriented usage

New approaches

Good formability Mg alloys
Materials which realize design for the environment
Lean structure material
Material of lower power-loss
Materials for static energy systems

Materials of higher resource productivity reduce the environmental load or resource consumption in the stage of usage of a product. Lightning material for automobile is a typical one. Mabuchi developed fine-grained Mg alloy which exhibits not only a good combination of higher strength and higher ductility at room temperature, but also higher formability at elevated temperature[15]. It is not limited to be lightning. A continuously variable transmission(CVT) is a superior automotive transmission that provides outstanding efficiency, which can improve the fuel efficiency greatly. [16] In this development the development of hard and tough material was the key of realizing the design of CVT which had been already proposed 10 years before

"Lean structure material" is the material to alleviate the load of the system. Adding to light metals and easy formable materials, shell structured materials are in development. "Material of lower power-loss" is a substance which can greatly reduce the loss which occurs on the inside and the surface of a substance by the transfer of energy and power. Superconductor, electro-magnetic steels are typical example. These materials are also expected in the area of friction, opt-electric, electric power device and so on.

Furthermore, materials are expected to be a source or media of static energy systems, which does not require extreme great energy input comparing with conventional dynamic energy systems. Solar cell, thermo-electric conductor, materials for cells including fuel cells and photo-catalysis are well known. Other series of energy conversion materials can be expected by controlling nano-size structure and interrelation of photon, phonon, spin and electron.

5. ACTION for STANDARDIZZATION

Now it is considered that we are at the stage of preparing the standardization of Ecomaterials. The background of the requirement of standardization is as follows.

1. Guidelines to implementation of ecomaterials is necessary to promote them.

Ecomaterials sometimes have disadvantages in cost or in properties because of the sacrifice of the reduction of environmental impacts.

These materials have sufficient properties in almost cases if they are used in the right place with DfE.

2. The standardization of quality and composition for recyclable material and its secondary raw material is required in focusing with man-made impurities.

Man-made impurities mixed in material's life deteriorate the property of recycled material

3. The test of stability and the analysis method of spoilage substance at the end of life are required in order to evaluate Ecomaterial through whole life stage.

The environmental impact data of materials in the end of life stage are little informed, ex. stability of substance including or coating material which sometimes change into hazardous substance through waste/recycling treatment with severe and complicated conditions.

Then, the standardization of ecomaterials will enhance the market and trade of new materials which are developed from the viewpoint of environmental consciousness by following points;

a) clarifying the quality-targets which newly developed ecomaterial should possesses.
b) presenting the fundamental information for designing with ecomaterials
c) indicating the proper utilization of ecomaterials considering their feature
d) promote the trade of useful raw material from treated waste and disassembled products

In order to achieve them, the criteria of properties in which each ecomaterial satisfies to use in the proper place are necessary, namely

- required properties for each appropriate application
- stability of mechanical/chemical characters

Therefore, the scope of the collaboration for the standardization should cover the scientific understanding of the required properties and characters of ecomaterials and the technological test method to examine them. Technological definitions of terms and measures for communicate these properties should also be put on the scope.

We have an appropriate organization to prepare the international standardization. The name of the organization is VAMAS (the VERSAILLES PROJECT on ADVANCED MATERIALS and STANDARDS). VAMAS was established by G7 countries after Versailles Summit to support trade in high technology products through international collaborative projects aimed at providing the technical basis for drafting codes of practice and specifications for advanced material. The scope of the collaboration in VAMAS embraces all agreed aspects of enabling science and technology – databases, test methods, design methods, and materials technology – which are required as a precursor to the drafting of standards for advanced materials. VAMAS supports world trade in products dependant on advanced materials technologies, through International collaborative projects aimed at providing the technical basis for harmonized measurements, testing, specifications, and standards. Founder Members of VAMAS are the government of Canada, France, Germany, Italy, Japan, UK, USA, and EC. And, VAMAS has about 30 TWAs(Technical working area) for each field of material.

At 1999, an approval on "VAMAS initiative on environmental standardization activities for materials technology " is discussed at the steering committee of VAMAS. As a result, "Definition of a Role for VAMAS Participation in Environmental Standardization Activities for Materials Technologies" was reported in VAMAS Bulletin No22. Through various events and achievements such as Ecomaterials Symposium in Canada 2000, International Ecomaterials Conference in Japan 1999, investigation of materials flow in U.S.A., linkage of LCA and STEP etc. and based on the hearing investigation on the industrial needs for standardization of Ecomaterials by Ecomaterials Forum Japan, a proposal of preparing a new TWA on ECOMATERIALs in VAMAS was proposed at 2001. Now it is the stage of prepare the framework of collaboration focusing on the standardization.

Japan government has been supported it by the project named "Ecomaterials Guideline in the era of global material flow" as a part of "global leadership promoting founding" of MEXT By this founding the International workshops on Ecomaterials was held three times in two years. General Guidelines which was discussed in the last workshop is as follows, and the parameters which are required to be standardized are also listed.

With the aim to develop a sustainable society we, materials scientists, propose to promote Ecomaterials production and use.
Sustainable society requires:
Sustainable Industrial Processes
Sustainable Transport (emission free)
Sustainable Energy (solar, wind, tidal, hydro-, biomass) (Sustainable Cities)
And
" Sustainable Life" (biomaterials: improve, extend life)
Ecomaterial is a material which contributes to a sustainable society.
Every material has the possibility to become an ecomaterial if properly selected and managed.
The Ecomaterials Group should prepare detailed guidelines and criteria for products and process designs for the environment.

General Ecomaterials Guidelines for Selection and Development[1]

1. An ecomaterial is the material of the highest efficiency to reach a sustainable society among the variants considered for a particular product and its application.

2. The highest eco-efficiency is given by the optimal combination of environmental, resource and technical efficiencies throughout the life cycle of the product.

3. In particular, an ecomaterial is associated with
- minimal health hazards
- minimal harmful emissions and wastes
- minimal energy requirement
- maximal recycleability and minimal material resource depletion
- optimal physical properties and best technical performance.

4. The total environmental, resource, social, societal and economic burden of an ecomaterial is the combined minimum taking into account the variants considered in a particular product throughout its life cycle.

The parameters to be expected to be discussed in standardization are as follows.

1. parameter of minimizing hazardous substance
a) content of hazardous substance in the material
b) recovery management efficiency of hazardous substance
2. parameter of green environmental profile
a) ratio of renewable resources
b) ratio of recycled resources
c) CO_2 emission until materials production
d) Ecological rucksack
e) Ecological footprint
3. parameter of recycleability of material
a) ratio of end-of-life material
b) possibility of open recycling
c) energy reduction effect by recycling
d) reduction of waste
4. parameter of resource productivity of material
a) resource productivity of input material
b) resource productivity of using phase
c) easiness of life-cycle management
5. parameter of purification effect of material
a) possibility of purification
b) life-time accumulation of removed pollutant

REFEREWENCES
[1] K.Halada,K.Ijima,N.Katagiri, and T.Ohkura, J. Japan Inst. Metals, Vol65.No.7 pp564-570 [in Japanese]
[2] K.Halada: Bulletin of Japan Institute of Metals 31(1992) 505-512 [in Japanese]
[3] K.Halada and R.Yamamoto: MRS bulletin 26 (2001) 871-879
[4] K.Halada: Current opinion in Solid State and Materials Science 7(2003)209-216
[5] K.Halada: Materials Science Forum Vols426-432 (2003)pp 4617-4622
[6] T.Shiga, "mercury-Free Flat Discharge Fluorescent Lamps", 2nd Workshop on Ecomaterials, Tsukuba 2002
[7] Y.Makita "β-$FeSi_2$ semiconductor as an alternative of GaAs" 2nd Workshop on Ecomaterials, Tsukuba 2002
[8] H.Cho et.al, Materials Science forum, vols 426-432(2003) 3329-3334
[9] T.Raja et.al., Materials Science forum, vols 426-432(2003) 4623-4628
[10] Y.Yoshimura et.al., Materials Science forum, vols 426-432(2003) 3359-3364
[11] Y.Zang et.al, [10] Y.Yoshimura et.al., Materials Science forum, vols 426-432(2003) 3365-3370
[12] S.Inada,K.Sato and T.Takai, "Chemical Recycling Process of PCR PET bottles for Completing the Closed Loop Recycling" 2nd Workshop on Ecomaterials, Tsukuba 2002
[13] Y.Osawa et.al, Materials Science forum, vols 426-432(2003) 3347-3352
[14] T.Fukushima,, Materials Science forum, vols 426-432(2003) 3323-3328
[15] M.Mabuchi, Materials Science forum, vols 426-432(2003) 3299-3304
[16] Y.Suzuki, "Role of material in development of CVT" 2nd Workshop on Ecomaterials, Tsukuba 2002

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