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Review paper

Economics of rare earth elements in ceramic capacitors

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Abstract

Ceramic capacitors are an indispensable component in electronic circuits, since they are used in various applications such as timing, filtering, and decoupling. These capacitors are doped with REEs that improve their operating life and electrical properties. In this paper, the economics of rare earth elements (REEs) are reviewed in light of their importance in ceramic capacitors. The developing rare earth element supply and demand crisis that can negatively impact the ceramic capacitor industry and, hence, the global economy, is explained. The cause of this crisis and the response of the world are also discussed.

Keywords: Rare earth elements; Ceramic capacitors; Barium titanate

Contents

1. Introduction

Rare earth elements (REEs) consist of the 15 lanthanide elements with atomic numbers (Z) 57–71, as shown in Fig. 1. The lanthanides consist of the following elements: lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu). The elements scandium (Sc) and yttrium (Y) have similar properties to lanthanides and are also included in the list of REEs, making seventeen REEs in total.

REEs are typically soft, malleable, ductile, and usually reactive at higher temperatures. These elements share

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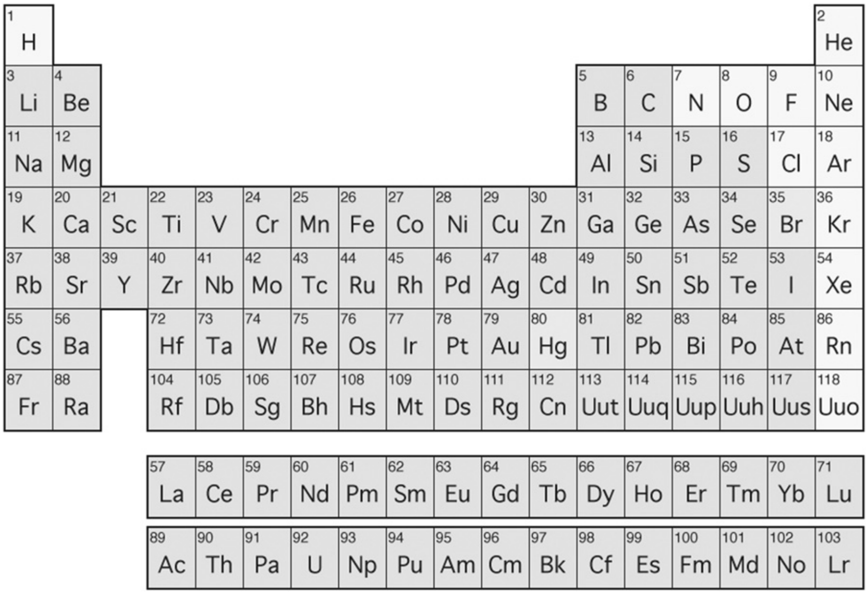

Fig. 1. Periodic table of the elements.

many common properties, which make them difficult to separate or distinguish from each other. The common properties of REEs are as follows:

- Generally silvery, silvery-white, or gray in color.
- Metallic luster is quite high, but gets easily tarnished in air.
- Occur naturally with minerals such as monazite.
- Have high electrical conductivity.
- Oxidation state is usually +3.
- Have similar ionic radii.

These 17 rare earth elements (REEs) are strategic resources upon which entire national economies are built. These elements are so valuable that many experts call them the fourth most important natural resources in the world, after oil, water, and iron ore. Adding these elements to more commonly available materials imparts special electrical, optical, and thermal properties. Therefore, REEs are used in a wide range of products. Life today as we know would not be possible without the use of REEs, or REE substitutes, once developed.

REEs were first isolated in the 18th and 19th centuries as oxides from rare minerals. The term “rare earth” is actually a misnomer. The elements are not rare and are found in low concentrations throughout the earth’s crust. The most commonly occurring rare earth elements, such as cerium, lanthanum, neodymium, and yttrium, are actually more common in the earth’s crust than lead and silver. Cerium (60 ppm), the most abundant rare earth element, is found on the earth’s crust in greater quantities than copper. Lutetium (0.5 ppm) and thulium (0.5 ppm), the least abundant rare earth elements, are also more prevalent on the earth’s crust than antimony, cadmium, thallium, and bismuth. The concentrations of REEs on the earth’s crust are shown in Table 1.

Table 1
Abundance of REEs on the earth’s crust [1].

Element	Symbol	Atomic number (*Z*)	Abundance in earth’s crust (ppm)
Yttrium	Y	39	22
Lanthanum	La	57	30
Cerium	Ce	58	64
Praseodymium	Pr	59	7.1
Neodymium	Nd	60	26
Promethium	Pm	61	–;
Samarium	Sm	62	4.50
Europium	Eu	63	0.88
Gadolinium	Gd	64	3.80
Terbium	Tb	65	0.64
Dysprosium	Dy	66	3.50
Holmium	Ho	67	0.80
Erbium	Er	68	2.30
Thulium	Tm	69	0.33
Ytterbium	Yb	70	2.20
Lutetium	Lu	71	0.32

Although REEs are abundant on the earth’s crust, extraction is complex. These elements can be found in almost all massive rock formations around the world, but their concentrations range from ten to a few hundred ppm by weight. These elements are spread around the world, and are rarely found in large concentrations. Finding them in a significant concentration where they can be economically mined is a challenge, and therefore these elements are known as rare earth elements. An examination of how REEs are processed results in a better appreciation and understanding of the difficulty in extracting them. In general, the extraction of REEs takes approximately 10 days from the time when the ore is mined to the time when the rare earth oxides (R_2O_3) are actually produced. The process flow for the extraction of REEs is shown in Fig. 2.

Currently, about 97% of the REEs are produced by China. Other countries that produce REEs in small

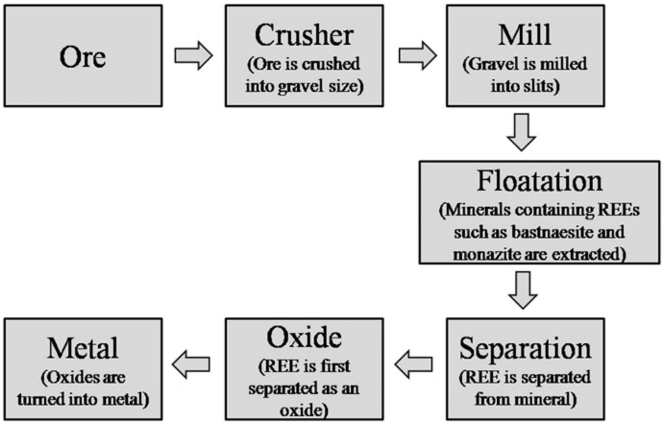

Fig. 2. Process flow for the extraction of rare earth elements [2].

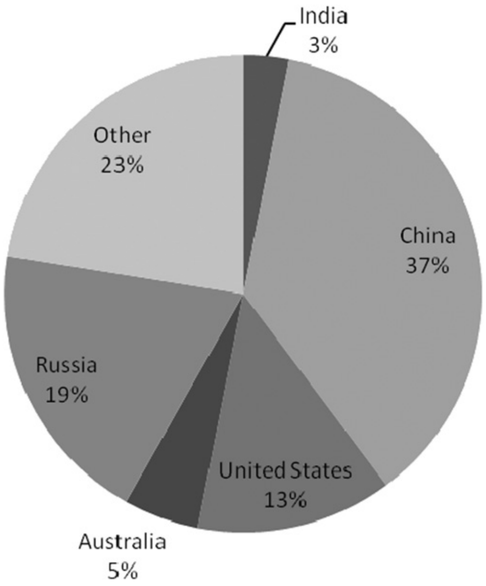

Fig. 3. Reserves of REEs by country [3].

quantities are India, Brazil, Sri Lanka, Russia, Malaysia, and Thailand. Although China produces most of the world's REEs, REE reserves are more dispersed throughout the world. China holds about 36% of the world's reserves (36 million metric tons out of 99 million metric tons), and the United States holds about 13%, as shown in Fig. 3.

The prices of REEs have been steady from the 1960s through the 1980s, when markets were created in response to new technologies and the REE sources remained relatively steady. In recent years, the prices of REEs can be considered inexpensive and have lagged behind inflation. The prices for individual REEs were generally lower in the late 1990s and early 2000s than those in the 1960s, 1970s, and 1980s. This decrease in prices was due to China's significant impact on the rare earth market starting in the 1990s. The prices of various rare earth oxides and rare earth elements (US$/kg) from 1963 to 2003 are given in Table 2.

2. Ceramic capacitors

This paper discusses the important applications of REEs as dopants in the dielectric of multilayer ceramic capacitors (MLCCs). MLCCs are an indispensable component in electronic circuits and are used in applications such as timing, filtering, and decoupling. The advantages of MLCCs include their small size, cost effectiveness, and stable performance over a wide range of frequencies. These surface mount devices (SMDs) are suitable for automotive, aerospace, defense, entertainment, medical, oil exploration, and telecommunication electronics applications. Common electronic products contain large numbers of MLCCs. For example, there are about 250 MLCCs in a cell phone, about 400 in a laptop, and over 1000 in

Table 2
Cost of REEs and oxides from 1963 to 2003 (US$/kg) [1].

	Year									
	1963		1973		1983		1993		2003	
	Oxide	Metal	Oxide	Metal	Oxide	Metal	Oxide	Metal	Oxide	Metal
Lanthanum	12	309	10	88	19	125	19	150	12	25
Cerium	17	304	11	88	20	125	23	350	18	30
Praseodymium	88	386	71	353	130	310	37	540	30	70
Neodymium	66	386	26	220	80	260	88	340	18	30
Samarium	99	397	66	298	130	330	66	300	58	80
Europium	1411	3307	992	5952	1900	7500	992	7600	1120	1600
Gadolinium	176	463	99	463	140	485	121	500	55	78
Terbium	860	2315	606	1543	1200	2800	827	2800	440	630
Dysprosium	187	661	88	265	110	300	132	500	90	120
Holmium	254	661	265	606	650	1600	485	1400	245	350
Erbium	187	664	99	309	200	650	143	725	135	180
Thulium	2756	8378	2205	5291	3400	8000	2750	6500	1950	3000
Ytterbium	331	1047	187	507	225	875	220	1200	360	484
Lutetium	7661	9370	4409	12125	5200	14200	5500	13000	2400	4000
Yttrium	119	717	66	309	94	430	80	340	52	96

automotive electronics [4]. Shipments of MLCCs have grown at an annual rate of about 15%, and the demand is expected to increase in the future [5]. In the United States alone, approximately 3billion MLCCs are used annually [6]. Recent advances in design and materials have even allowed MLCCs to replace electrolytic capacitors in certain applications, such as filtering [7].

MLCCs are made up of alternating layers of metal electrodes and ceramic dielectric, as shown in Fig. 4. Typically, perovskites (ceramics with a general formula of ABO_3) are used as the dielectric material due to their high dielectric constant [8]. Among perovskites, barium titanate ($BaTiO_3$) is the most widely used material because of its excellent dielectric properties [9]. The crystal structure of $BaTiO_3$ is shown in Fig. 5, in which the Ba atom is at the A-site and the Ti atom is at the B-site.

2.1. History of dopants in multilayer ceramic capacitors (MLCCs)

In the 1970s and 1980s, precious metal electrodes (PMEs) composed of elements such as palladium (Pd) and silver (Ag) were widely used in MLCCs, but the price of Pd increased by a factor of 10 between 1992 and 2000. To reduce the cost, base metal electrode (BME) materials such as nickel (Ni) and copper (Cu) were introduced. A problem with the use of BMEs was that the dielectric of these capacitors must be fired in a reducing atmosphere (low oxygen partial pressure) to protect the electrode material (Ni/Cu) from oxidation. But, in a reducing atmosphere, the ceramic ($BaTiO_3$) was reduced, leading to the formation of doubly charged ionized oxygen vacancies, which can be expressed as

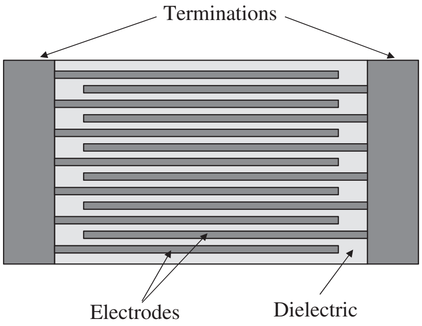

Fig. 4. Multilayer ceramic capacitor.

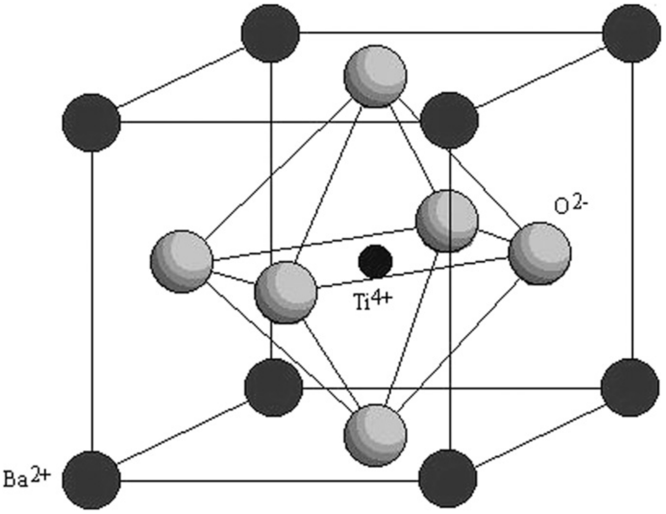

Fig. 5. Crystal structure of barium titanate.

$$O_O \rightarrow \tfrac{1}{2}O_2\uparrow + V_O^{oo} + 2e^- \qquad (1)$$

where O_o is an oxygen atom at the oxygen site, O_2 is the liberated oxygen, V_o^{oo} is a doubly positively charged oxygen vacancy, and e^- is an electron. Due to the generation of these charge carriers, the insulation resistance of the dielectric was found to decrease. Further, in a reducing atmosphere, reduction of Ti^{4+} to Ti^{3+} can also take place, leading to a semiconducting behavior. The initial solution to this problem was the addition of transition metal ions (Fe^{3+}, Mn^{2+}, and Cr^{3+}) that acted as strong electron acceptors on the Ti-site. Due to a high activation energy (≈ 2 eV) [10], the conduction electrons were deeply trapped by the addition of these acceptors, and a higher insulation resistance was maintained. The trapping of the conduction electrons can be expressed as

$$[Mn_{Ti}^{2+}] + 2e^- \rightarrow [Mn_{Ti}^{2+}]'' \qquad (2)$$

where Mn_{Ti}'' represents a doubly negatively charged Mn atom substituting the regular lattice site of the Ti atom. Another acceptor dopant was Ca^{2+} on the Ti site. The addition of acceptor dopants increased the insulation resistance of the dielectric fired in a reducing environment, but the insulation resistance of this dielectric was degraded under temperature and voltage stress conditions. This phenomenon led to numerous MLCC failures in the 1970s. This degradation was attributed to the motion of oxygen vacancies [11]. However, the stability of BME capacitors during temperature and voltage aging was found to improve by a gentle re-oxidation treatment that affected the mobility of oxygen vacancies.

Around 1990, a new generation BME dielectric materials were developed, which contained mixtures of donors (such as Nb and W) and acceptors (Mn and Cr) [12]. Due to the interaction between donors and acceptors, the electromigration of oxygen vacancies was suppressed. In these materials, the donors and acceptors formed highly stable complexes which could no longer be oxidized, even in a pure oxygen atmosphere. The donors reduced the number of oxygen vacancies and acted as strong barriers against their migration. The formation of these highly stable complexes can be expressed as [13]

$$[Mn_{Ti}^{3+}]' + [Nb_{Ti}^{5+}]^{o} \rightarrow \{[Mn_{Ti}^{3+}][Nb_{Ti}^{5+}]\} \qquad (3.1)$$

$$[Mn_{Ti}^{2+}]'' + [W_{Ti}^{6+}]^{oo} \rightarrow \{[Mn_{Ti}^{2+}][W_{Ti}^{6+}]\} \qquad (3.2)$$

A major breakthrough was achieved when the addition of rare earth dopants intermediate in size led to improved life characteristics. The lifetime under elevated temperature and voltage conditions (150 °C, 10 kV/mm) was found to be the best for Dy-doped $BaTiO_3$ [14]. In addition to the improved life characteristics, capacitors with REE dopants have better electrical properties. A stable capacitance ($\pm 15\%$) is observed over a wide range of temperatures (-55 to 150 °C) with the incorporation of these REEs. The most stable capacitance was observed in dielectrics doped with smaller ionic radii rare earth elements, such as Yb and Lu [15]. The addition of REE dopants can also lead to an increase in the dielectric constant of $BaTiO_3$. A dielectric constant as high as 4308 was obtained in a ternary system of $BaTiO_3$–Nb_2O_5–Fe_2O_3 at 3.846 wt% of La_2O_3 [16]. Further, the dissipation factor of the dielectric was found to decrease with the incorporation of REEs such as Er and Yb [17].

3. Rare earth element (REE) dopants in multilayer ceramic capacitors (MLCCs)

REEs are sometimes referred to as "magic dopants" and are amphoteric (i.e., they can substitute at both A and B sites in a perovskite lattice) [18]. The site substitution depends on the ionic radius of the rare earth ion (which is given in Table 3) and the A/B ratio. Since the charge difference of the trivalent rare earth metal is ± 1 for both A and B sites, the ionic radius will be the deciding factor for site occupancy. REEs with smaller ionic radii (e.g., Dy, Ho, Er) substitute for the Ti ion (whose ionic radius is 0.605 Å), or B-site. REEs with larger ionic radii (e.g., La, Sm) substitute for the Ba ion (whose ionic radius is 1.610 Å), or A-site. REEs with intermediate ionic radii can substitute for both the Ti and Ba ions depending on the Ti/Ba ratio. This can be explained by writing the defect reactions of substitution of the rare earth oxide (R_2O_3) at the A and B sites of $BaTiO_3$ [19]:

$$\tfrac{1}{2}\,R_2O_3 \rightarrow R^{o}_{Ba} + V''''_{Ti} + \tfrac{3}{2}\,O_O + \tfrac{3}{2}V^{oo}_{O} \times (\text{A site substitution, R substitutes for Ba}) \tag{4.1}$$

$$\tfrac{1}{2}\,R_2O_3 \rightarrow R'_{Ti} + V''_{Ba} + \tfrac{3}{2}\,O_O + \tfrac{3}{2}V^{oo}_{O} \times (\text{B site substitution, R substitutes for Ti}) \tag{4.2}$$

Combining the mass action relation of Eqs. (4.1) and (4.2) gives

$$\frac{[R^{o}_{Ba}]}{[R'_{Ti}]} = K\,\frac{[V''_{Ba}]}{[V''''_{Ti}]} \tag{5}$$

From the above Eq. (5), it follows that a Ba-rich phase will lead to a B-site substitution and a Ti-rich phase will lead to an A-site substitution. It is to be noted from these Eqs. (4) and (5) that the experiments were held at high temperatures during sintering when these species were mobile.

The electrical properties of MLCCs with perovskite dielectric are found to improve with the addition of REEs. The mechanisms that lead to an improvement in the electrical properties are discussed in this section.

Table 3
Ionic radii of rare earth elements (12 coordinated).

Light weight rare earth ions with large ionic radii						
La^{3+}	Ce^{3+}	Pr^{3+}	Nd^{3+}			
0.123	0.115	0.114	0.112			
Middle weight rare earth ions with large ionic radii						
Sm^{3+}	Eu^{3+}	Gd^{3+}	Tb^{3+}	Dy^{3+}	Ho^{3+}	Er^{3+}
0.106	0.106	0.104	0.100	0.099	0.098	0.096
Heavy weight rare earth ions with small ionic radii						
Tm^{3+}	Yb^{3+}	Lu^{3+}				
0.094	0.093	0.092				

3.1. Effect on insulation resistance and lifetime

The insulation resistance of REE-doped $BaTiO_3$ depends on the oxygen partial pressure and radius of the REE [20]. In a reducing atmosphere, intermediate ionic radii REE (Dy, Ho, and Er) doped samples have a higher conductivity than that of larger ionic radii REEs (La, Sm, and Gd), as shown in Fig. 6. However, in a slightly oxidizing atmosphere (not enough to oxidize the Ni), intermediate ionic radii REE-doped samples have a lower conductivity than that of larger ionic radii REEs. Intermediate ionic radii REE-doped $BaTiO_3$ dielectric in a slightly oxidizing atmosphere also has a higher lifetime during the life test (temperature and voltage stress).

When REEs substitute at the A-site, they act as donor, and when REEs substitute at the B-site, they act as acceptor. The incorporation of rare earth oxide (R_2O_3) in $BaTiO_3$ can be expressed as

$$\text{A site}: R_2O_3 \rightarrow 2R^{o}_{Ba} + V^{2}_{Ba} + 3O_O \tag{6.1}$$

$$\text{B site}: R_2O_3 \rightarrow 2R^{¢}_{Ti} + 2O_O + V^{oo}_{O} \tag{6.2}$$

The increased life by addition of these ions can be explained by the A- and B-site models [19]. The A-site model suggests that these dopants act as donors and

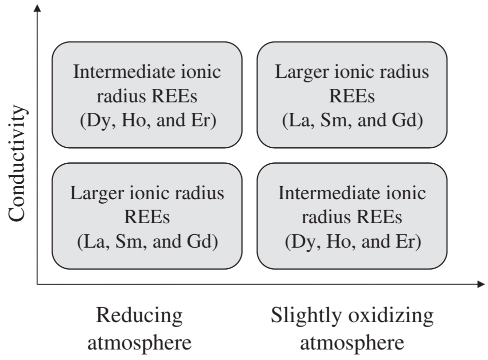

Fig. 6. Effect of doping REE in $BaTiO_3$.

improve the reliability by reducing the concentration of oxygen vacancies. The B-site model suggests that these dopants act as acceptors and improve the reliability by reducing the diffusion of oxygen vacancies. The amphoteric REE helps balance the donor and acceptor, so the lifetime of the MLCC improves with the addition of the REE.

3.2. Effect on capacitor aging

The change in capacitance after 1000 h of a temperature and voltage aging test at 40 °C and 50 V was small in MLCCs doped with REEs of intermediate ionic radius (Dy, Ho, and Er), compared to MLCCs doped with REEs of larger ionic radius (La, Sm, and Gd) [20]. This result was explained by an increase in the concentration of oxygen vacancies in REEs with a larger ionic radius.

3.3. Effect on Curie temperature

The Curie temperature of $BaTiO_3$ doped with various REEs was measured using a differential scanning calorimeter (DSC) [21]. It was observed that the DSC peaks broadened and shifted to higher temperatures by the doping of smaller ionic radius REEs, such as Ho, Er, Yb, and Lu. The DSC peaks are due to the Curie temperature of the core. A higher diffusivity of smaller ionic radius REEs (Lu and Yb) into the core phase is expected to flatten and shift the tetragonal to cubic transition to a higher temperature. MLCC dielectrics with a flat tetragonal to cubic transition and a higher Curie temperature can be used for high temperature applications.

3.4. Effect on temperature coefficient of capacitance (TCC)

When the temperature coefficients of capacitance (TCCs) of various REE-doped $BaTiO_3$ capacitors were measured [21], it was found that the TCC increased with a decrease in the ionic radius of the REE. However, the change in capacitance of all REE (Pr, Gd, Ho, Er, Yb, and Lu) doped capacitors was within $\pm 15\%$ over a wide range of temperatures (-55 to 150 °C), satisfying the X8R requirement for high temperature applications. In another study, the optimum concentration of rare earth oxide (Ho_2O_3) in $BaTiO_3$ was found to be about 1% by weight, which satisfied the X7R requirements ($\pm 15\%$ from -55 °C to $+125$ °C) [22]. This behavior is due to the formation of the core–shell structure [23]. The shell phase is composed of both the dopants and $BaTiO_3$, and the core is almost pure ferroelectric $BaTiO_3$. The non-ferroelectric shell phase stabilizes the capacitance. For the formation of this core–shell structure, MgO is also added [24]. The microstructure of $BaTiO_3$–MgO–R_2O_3 controls the electrical properties, which depend on the MgO/R_2O_3 ratio, the firing condition, and the ionic radii of the REE [25].

4. Rare earth element crisis

From 1965 to 1985, most of the world's REEs came from Mountain Pass, California. Australia was also a major producer of REEs until the early 1990s [26]. But, during the 1990s and for much of the past decade, China was able to produce REEs more economically than other countries, which led to the closure of Australian and US mines. Today, most REEs are mined and produced from China's Bayan Obo deposit in inner Mongolia. Currently, China controls approximately 97% of the world's rare earth element market.

With a population of 1.3 billion and the fastest growing economy in the world, China is facing the challenging task of ensuring that it can meet both the domestic REE demand for continued economic growth, and the international export demand. To do so, China has been limiting REE exports by establishing quotas and banning the sale of some REEs outside the country. In July 2010, China's ministry of commerce announced that China would cut its export quota for REEs by 72% [27]. At the end of 2010, the Chinese government announced that REE export quotas for the first half of 2011 would be decreased by 35% [28]. China's policy goals are to obtain a constant supply of REEs for its domestic economy and cut down on overproduction, illegal mining, and smuggling [29]. Currently, the global demand for all REEs is about 134,000 t /year and the global production is about 124,000 t /year. This deficit of 10,000 t is covered by inventory reserves. Global demand for REEs is expected to rise to 180,000 t /year by 2012 and may exceed 200,000 t /year by 2014.

The REEs for which China has restricted export quotas are dysprosium, terbium, thulium, lutetium, yttrium, and the heavy and scarcer REEs [30]. Among these REEs, dysprosium is widely used in MLCCs, since it improves insulation resistance and life. Dysprosium is also in the list of five REEs that are critical to energy applications, according to the US Department of Energy (DoE) [29].

A shortage of REEs will affect the ceramic capacitor industry, which will eventually affect the electronics industry that consumes about 18% of these REEs [31]. This supply versus demand crisis can lead to higher prices of various electronic commodities, which in turn can also affect the global economy. As shown in a September 2010 World Bank Policy Research Working Paper, the electronics industry is the world's most important goods-producing sector. Not only does it employ more workers and generate greater revenue than any other sector, but also its products enhance productivity in other activities and stimulate innovation across entire economies. Electronics components are a propulsive sector, in that they are a driving force in the global economy. They account for a significant portion of global economic activity, have strong linkages to other industrial sectors (in terms of transacting business with other local businesses), and have a high level of export/import activity associated with their goods and services. Using the most recently available comprehensive global trade statistics in their study of the evolution of global value chains in the electronics industry, Sturgeon and Kawakami [32] illustrated the increasingly important role the electronics industry has played in global value chain formation since 1988. The share of electronics intermediates (including semiconductors and printed circuit boards) has grown dramatically from 1988 to 2006, from 24.4% of the top 50 products, to 43.3%. As a result, the growth rate of electronics intermediates was the highest in the top-50 product groupings (13.8% per year). In short, without electronic circuits, the global economy ceases to function.

4.1. Response of the world to the REE crisis

In view of the vital economic importance of REEs and in response to China's embargoes, alternative supply initiatives are rapidly emerging. Mongolia is developing a number of joint venture projects with foreign investors to ensure that alternative REE supplies are made available for demands outside of China. REE export supply routes from Mongolia to the west through Vladivostok are also expected to have a major impact on the near-term development of that strategic port. According to Chris Devonshire-Ellis of the consulting firm Dezan Shira and Associates [33] "the Mongolian initiative may well pave the way for a rebirth of the port in response to concerns over the sustainability of Chinese supplies (of REEs) and the tendency to politicize trade through the barring of exports and closing of borders." Rarely does a short term event cause such a rapid reaction in alternative trade developments, as China's 2010 embargoes of REEs has. This demonstrates the importance of REEs to the global economy.

In the US, Molycorp renewed the Mountain Pass mining permit and began R&D of its own in 2004. In 2011, Molycorp planned to sell 3000 t of REE ore that was mined before the previous permit expired. By 2012, Molycorp expects to produce 20,000 metric tons a year. The company will produce REE products at half the cost of Chinese-produced REEs through process changes and the use of a closed-loop system, in which the chemical wastes will be reused. The company will also install a natural gas cogeneration power plant onsite to cut energy costs [34].

Australia's REE policy goal is to balance a stable investment environment that promotes the REE mining industries [29]. The Australian government offers tax rebates to REE mining companies for exploration and levies low taxes on extracted REEs. Arufura Resources, an Australia-based REE mining company, has drawn foreign investments, with Chinese investors taking a majority stake in the company. Lynas Corporation, another Australian company, owns the world's richest REE reserves at Mt. Weld [35].

Japan is trying to reclaim REEs from recycled electronics and batteries and develop alternative supplies of REEs found in Mongolia. Japan has accelerated its search for new suppliers around the world. Its annual demand for rare earth elements is more than 30,000 metric tons, and it currently depends on China for about 90% of its supply [36]. The Toyota Motor Corporation has established an REE task force to monitor its supply chain. Toyota planned to start developing REEs in India in 2011, and in Vietnam in 2013 [37]. Japan also plans to step up its search for REEs in deep-sea mud that contains high concentrations of REEs at numerous sites in the Pacific ocean [38].

India is also planning to revive its production of REEs. However, the country has said it will only be filling the gap in the market left by China's falling exports. Indian Rare Earths Limited (IREL) halted its output in 2004 in the phase of Chinese competition. It is now reviving its business with a modest investment of 1.4 billion rupees (US$31.9 million) in a 5000 metric ton plant, which it hopes will begin production in 2012 [39].

5. Conclusions

Ceramic capacitors are an indispensable component in electronic circuits, and approximately three billion ceramic capacitors are used annually in the U.S. alone. All these capacitors are doped with REEs of intermediate ionic radii (such as Dy, Ho, and Er), since they improve the operating life (reliability) and electrical properties of the ceramic capacitors. The improvements in electric properties are a lower dissipation factor, lower aging rate, and a stable capacitance over a wide temperature range. REE-doped capacitors also satisfy the X8R requirements for high temperature applications, such as down hole (oil exploration), automotive (under hood), military, and aerospace applications. The advantages of REE dopants in ceramic capacitors make REEs some of the most critical elements in the electronics industry.

Given the shortages in the supply of REEs, the prices of REEs will climb significantly. Although new sources of REEs are currently being developed, the DoE's analysis is that new mines will only provide an additional 12% of dysprosium by 2015.The supply restrictions and increasing cost of REEs are expected to be magnified throughout the entire supply chain of the electronics industry. The higher prices of REEs will be reflected in the increasing cost of consumer, automotive, medical, aerospace, and defense electronics if no substitutes are found.

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